Bulletin
of
The Geological Society of America

VOLUME 63 August 1952 NUMBER 8

CONTENTS

	Page
Relations between the mechanism of the formation of fault troughs and volcanic activity. By B. G. Escher	749-756
Age of the Bear River formation, Wyoming. By Teng-Chien Yen	757-764
Table for computing thickness of strata measured in a traverse or encountered in a bore hole. By Hugo Mandelbaum and John T. Sanford	765-776
Seismic-refraction measurements in the Atlantic Ocean. Gart IV—Bermuda, Bermuda Rise, and Nares Basin. By C. B. Officer, Maurice Ewing and P. C. Wuenschel	777-808
Stratigraphy in the Permo-Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico. By Kenneth C. Brill, Jr.	809-880
Short Note	
Foraminifera in glacial till from northeastern Montana. By Clifford A. Kaye	881

Subscription $15.00 per year.

Publication Office: Mt. Royal & Guilford Aves., Baltimore 2, Md.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117 Street, New York, N. Y.

NOTICE—Four weeks notice of change of address is necessary. In accordance with the rules established by the Council, claims for for non-receipt of the preceding number of the Bulletin must be sent the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter at the Post-Office at Baltimore, Md., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103 Act of October 3, 1917, authorized on July 8, 1918.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

Late Quaternary Geology and Frost Phenomena Along the Alaska Highway, Northern British Columbia and Southeastern Yukon. By Charles S. Denny

Gravity and Magnetic Investigation of the Structure of the Cortlandt Complex, New York. By Nelson C. Steenland and George P. Woollard

Correlation of the Jurassic Formations of North America, Exclusive of Canada. By Ralph W. Imlay

Correlation of the Cretaceous Formations of the Western Interior of the United States. By William A. Cobban and John B. Reeside, Jr.

Problem of Glaciation in the Western Islands of Arctic Canada. By John L. Jenness

Drift Dispersion in West-Central New York. By Chauncey D. Holmes

Dynamic Basis of Geomorphology. By Arthur N. Strahler

Submarine Topographic Echoes from Explosive Sound. By B. Luskin, M. Landisman, G. B. Tirey, and G. R. Hamilton

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 749-756 AUGUST 1952

RELATION BETWEEN THE MECHANISM OF THE FORMATION OF FAULT TROUGHS AND VOLCANIC ACTIVITY

By B. G. Escher

(Presidential Address, International Association of Vulcanology, Brussels, 1951)

Abstract

First, the attitude and nature of the border faults of typical grabens are examined. In the Lorettoberg tunnel, the master fault that bounds the Rhinegraben on the east side (Schwarzwald) dips 55° toward the graben. It is a crushed zone 15 m. wide. The border faults of the 30 km. wide Central Graben of the Netherlands (Roer Valley) dip grabenward 50°–65° on the southwest side and 50° on the northeast side. They are accurately known from explorations in the coal fields. The crushed zone is 5 to 30 m. wide on the Heerlerheide fault and 40 to 200 m. wide on the Feldbiss fault. The dip slip on the former is 250 m., on the latter 500 m., suggesting a correlation between length of dip slip and width of crushed zone.

Such facts, combined with the existence of antithetic faults along the master fault on the west side of the Rhinegraben, as shown by Hans Cloos, are best explained by a tensional origin of grabens, especially when combined with Hans Cloos' concept of regional doming and Le Conte's way of accounting for the uptilt of graben borders.

De Sitter and Van Riel have shown that negative gravity anomalies exist over the Roeg Valley just as they do over the Rift Valley of East Africa, according to Kohlenschütter and Bullard. Vening Meinesz and Goguel have shown that these anomalies do not require compression for an explanation, as asserted by Bullard and Holmes.

In the second part of the paper, the results of recent work on the products of volcanism in East Africa are analysed and thought to be consistent with a tensional origin of the grabens. There is a decided resemblance with Iceland and Hawaii, recently pointed out by Verhoogen, Tazieff, and De Magnée. It includes the presence of Great Shield Volcanoes, fissure eruptions yielding very fluid lava, volcanoes lined up along a fracture, and pit craters and "volcanic sinks."

Then there is the great preponderance of basic over acid lavas, apt to be obscured, if the multiplicity of rock types is viewed without regard to relative abundance. In the lava field north of Lake Kivu, *e.g.*, the ratio of basic to acid lavas is 240:1.

The progressive changes in the lavas of some volcanoes (Biega and Kahusi, described by Sorotchinsky, and of Bufumbira, according to Holmes and Harwood) are interpreted as the result of the eruption of magma derived from a basic vitreous substratum progressively altered by assimilation of pre-existing rocks in the crust. It is unlikely that magmatic differentiation has played an important role in areas of great tensional grabens; it belongs to areas of compressional folding.

CONTENTS

TEXT

	Page
Introduction	750
Border faults	750
Attitude of border faults	750
Rhine graben	750
East African rift system	750
Roer valley graben	751
Nature of border faults	751
Tensional origin of border faults	751
Volcanism of fracture belts	752
East Africa compared with Iceland and Hawaii	752
Effusive rocks of East Africa	753
Need for volume estimates	753
Local multiplicity of rock types	753
Basaltic parent magma and Earth's crust	753
Effusive rocks of Arabia and Syria	754
Conclusions	754
References cited	754

Introduction

The choice of the subject for my address has not been difficult in view of the work done by our Belgian colleagues in the eastern province of Belgian Congo, in Ruanda, and in Uganda. As some of them have investigated the recent vulcanism north of Lake Kivu, the obvious thing to do is to spend some moments on the relation between the mechanism of the formation of fault troughs or grabens and volcanic activity. It is not my intention to go into details, which are so well known to our Belgian colleagues, and which I hope to hear treated by them in the sessions of our association. I intend only to summarize the theories which try to explain the formation of grabens and to show the relation between their location and volcanic activity.

I will begin by recalling what Eduard Suess, the Viennese master, wrote on the great African fault zone which stretches from 15° S. Lat. over a length of 6000 kilometers to 37° N. Lat. as far as the Taurian Mass in Asia Minor:

> "An event which manifests itself over more than 52 degrees of latitude must find its reason for existence in the peculiarity of the planet itself. We arrive, for this broad region, at the acceptance of tensions in the outermost covers of the terrestrial sphere which have manifested themselves perpendicular to the direction of the fractures, here perpendicular to the meridian." (Translation, Suess, 1909, p. 316)

It seems to me that this judgment still holds value, even if we do not agree with the succeeding paragraph:

> "This is rending by contraction, by opening of the fissures from the surface downwards."

Here we are in the midst of the fight on the origin of fault troughs. Having given up the contraction theory, we are obliged to find another explanation for this problem. Three explanations have been brought forward to account for either the fault troughs of East Africa, or that of the Dead Sea, or that of the Rhine between Vogesen and Schwarzwald: (1) compression, (2) tension, and (3) vertical dilation. This last explanation we owe to Willis (1936) who conceived it in connection with his notion of asthenoliths. I think that we may abandon this theory, as it cannot explain the morphology of the East African system of rift valleys. The other two attempts to explain the fault troughs, by compression and by tension, are old.

Border Faults

Attitude of Border Faults

Rhine graben.—If it were always possible to measure the dip of the master faults which border a fault trough, the problem would be more or less solved. W. Salomon (1911; 1927) and his pupils measured the dip of the faults in the Rhine graben. H. Cloos (1932) has proved, both by measurements in the field and by experiments, that every master fault with great slip is accompanied by numerous faults, some of which dip in the same direction as the master faults and some in the opposite direction; these he called, respectively, synthetic and antithetic faults. The master fault bordering the Schwarzwald on the west side has been found in the tunnel through the Lorettoberg. It dips toward the graben at 55° (Brill, 1933). The crushed zone of this master fault is 15 meters wide.

East African rift system.—The paramount question here is whether the master faults on both sides of the fault trough converge or diverge under the graben. Bailey Willis (1936) does not mention the dip of the bordering faults in his great work on the East African Rift system. Still it is evident that the formation of a fault trough by compression must result in two border faults diverging downward, whereas their formation by tension would yield two border faults converging downward. As the angles of dip of the master faults are generally not known, it has been supposed that the question could be resolved by gravity measurements. E. C. Bullard (1936) has made these determinations, crossing the grabens of Lake Albert, Lake Tanganyika, Rukwa, and Magadi, and has found negative anomalies in each case. For the rest E. Kohlenschütter (Krenkel, 1925, Taf. XVII, p. 240) had already proven the negative anomalies for the graben of Lake Njassa, Lake Tanganyika, and the Gregory Rift Valley east of Lake Victoria. Bullard and A. Holmes (Holmes and Harwood, 1937) have concluded from these observations that the fault troughs must have been formed by lateral compression. But other geophysicists—*e.g.*, J. Goguel (1949)

and F. A. Vening Meinesz (1950)—deny the validity of their reasoning. It is quite possible to interpret a negative anomaly, observed in the fault trough, as due to light sediments at and near the surface of a graben formed by tension.

Roer valley graben.—Here I must point out a fact of utmost importance to our problem. The gravity measurements made in the southeastern part of the Netherlands have demonstrated that the fault trough of the Roer valley, which is also called the Central Graben of the Netherlands, shows a negative gravity anomaly (L. U. de Sitter and W. J. van Riel, 1949), while the very accurate examination of the structure of the Carboniferous in the coal mines has demonstrated that the fault zone, which borders this fault trough to the southwest, shows a dip of 50°–60° toward the northeast—that is, toward the middle of the graben.

With the aid of torsion-balance measurements the dip of the Peel boundary fault, which borders the same graben to the northeast, was found to be 50° toward the southwest—that is, toward the middle of the graben. Moreover in the German Coal Mine, Sophia Jacoba, this fault also dips 50° to the southwest (L. U. de Sitter, 1949, p. 65–79, 282–286). This fault trough has a width of 30 km. It is the northwest continuation of the Rhine graben. It is proved, then, that the reasoning of Bullard and Holmes is not valid in the case of the Roer valley graben and thus presumably not in the other typical graben regions. Bailey Willis (1928) introduced in his paper on the Dead Sea Problem the idea of "ramp valleys", as opposed to the "rift valleys" of Gregory. This concept makes the formation of fault troughs by lateral compression less improbable, because he assumes the diverging master faults bend back at depth toward the horizontal direction.

As a geologist, I believe the figure A. Holmes (1945, p. 439, Fig. 231) borrows from E. J. Wayland (1929) is altogether inacceptable, whereas Bailey Willis' idea of a ramp valley is at least conceivable as a result of horizontal compression. Nevertheless it seems to me that the only solution of our problem is to assume horizontal tension.

Much can be learned from the normal faults of the coal basin of Netherland's Limbourg District. During the last war they were studied in great detail by a group of young Dutch geologists in all mines of this district, and therefore they are among the best-known faults. They were studied at the surface, at different mine levels, in the drives, and by bore holes from the drives in more or less horizontal direction, and also by vertical drill holes from the surface. Of the three big step faults—Feldbiss, Heerlerheide, and Benzenrade—the first two are the best known. The dip of the Feldbiss toward the graben of the Roer is 65°; the two other faults dip in the same direction. The maximum dip slip of Feldbiss is 500 m., that of Heerlerheide fault 275 m., and of Benzenrade fault 250 m. (H. G. J. Sax, 1946; L. U. de Sitter, 1949; M. G. Rutten, 1943; F. Heybroek, 1947).

Nature of Border Faults

I must draw the attention of geophysicists to the fact that big faults with great dip slips are never a single plane, but always a shear zone with many more or less parallel faults; they are at the same time crushed zones. There is a certain relation between the width of a fault and its dip slip. This width is not constant along the fault; for the Heerlerheide fault the width changes between 5 and 30 meters. The Feldbiss is a shear zone of 40 to 200 m. in width, as far as is known. These facts have not found their way into the seismological literature. It seems to me especially important when considering the hypothetical thrust fault which borders the Pacific.

This important border fault, then, must represent a shear zone, the width of which measures probably tens of kilometers. Seismologists have tried to project the foci of strong deep circumpacific earthquakes on a single fault plane, ascribing the differences in horizontal direction to uncertainties in the determination of latitude and longitude. These certainly exist, but very probably the foci are really distributed horizontally over a considerable width. This general condition should also come into consideration in the very interesting speculations on aftershocks (Benioff, 1949; 1951).

Tensional Origin of Border Faults

As was mentioned already, the idea of the origin of fault troughs by tensional forces is

quite old. S. Taber (1927) gave it its return to life, as did H. Cloos (1929), who connected the origin of grabens with a doming of the earth's crust (H. Cloos, 1939), which he has demonstrated for the Rhine graben and its continuation to the north. But this combination of ideas was already advocated by the American geologist J. Le Conte (1889). He refers the reader to W. Hopkins (1842) who seems to have been the first to give an explanation of the tensional strain which seems to us, a century later, still the best. But Le Conte goes further into details and explains also the tilting of the two edges of a fault trough. He explains their uplift as a consequence of the shape of the blocks of the earth's crust, in combination with the law of Archimedes. In that way the drowned area of Lake Victoria and Lake Kioga finds a very simple explanation. It is the result of an upheaval east of the graben Kivu-Edward and west of the Gregory Rift Valley. H. Cloos also has given the same explanation for this crustal sag in the middle of the East African zone of fractures.

Volcanism of Fracture Belts

East Africa Compared with Iceland and Hawaii

Before leaving our tectonic considerations, I wish to draw attention to my conviction that all big faults of the fractured regions of the earth are extremely ancient and that they date from that great event—the separation of the moon from the earth—about which I spoke to you in Oslo (Escher, 1949a; 1949b). The fact that all big regions with fault troughs are accompanied by effusions of lava and by Volcanoes, which, for the greater part, are extinct, but which here and there are still active, points to the obvious connection between horizontal tension in the earth's crust and extrusion of magma. It would seem much less probable that volcanic gas and lava would escape from a zone where compressional forces exist. I will not here enter into details of the volcanism in folded regions for which I tried to give an explanation some 20 years ago (Escher, 1933).

The following active volcanoes are known in the African fractured region: Alu, Gabuli, Hertale, Ummuna, Dubbi, Afdera (Ethiopia); Teleki, Lengai, Meru (east of Lake Victoria); Nyamlagira and Nyiragongo (Virunga Volcanoes), (west of Lake Victoria). Moreover there are a great number of extinct volcanoes, for instance Kilimandjaro, Kenya, Elgon, the "giant craters" between Lake Eyasi and Lake Natron, Ngorongoro and Ololmoti, two shield-shaped lava volcanoes, and many others.

Through the papers of our Belgian colleagues J. Verhoogen (1939), H. Tazieff (1948; 1949a), and I. de Magnée (1948) on the recent eruptions of Nyamlagyra, we have learned that there is a certain analogy with the volcanism of Iceland and Hawaii; it does not resemble the volcanism of folded regions. It is a volcanicity typical of regions where tensional forces are at work, characterized by great shield volcanoes with gentle slopes, very liquid lava flows and pit craters, and the "volcanic sinks" of R. A. Daly (1933, p. 168), which are quite different from calderas. The first-named are connected with the eruption of basic lava, the latter with an acid magma. Here, in the Kivu region, there has been, as we will see, contamination of magma by assimilation of underlying rocks in the graben. It seems to me that here is the cause of the mixed volcanism of the African fracture zone.

Besides shield volcanoes, which are typical for Hawaii and Iceland, we find here volcanoes riding a crevice, as in Iceland, and ordinary normal cones, which never are formed by pure basic magma.

The last eruption of the volcanoes Kituro and Mahuboli, north of Lake Kivu, from the description of Tazieff (1948), somewhat resembled that of Hekla in Iceland (S. Thorarinsson, 1950). It was a fissure eruption, 7 kilometers long. It expelled very fluid lava flows with a length of 8 and 10 kilometers. Nyiragongo is a volcano with a pit crater, as found in Hawaii, and is in continual activity (Tazieff, 1949a). This pit crater is not on the top of a shield volcano, but at the summit of a basaltic cone with external slopes of 40°–60°. As far as the quantities of volcanic products are concerned, the outpourings of lava are the most important. They extend north and south of Lake Kivu, to the east and west of the fault trough from Lake Natron to Lake Rudolf, and include also the big lava sheets in Ethiopia, Arabia, and Syria.

I need not discuss the well-known volcanic products of the Rhine graben and of the Auvergne.

Effusive Rocks of East Africa

Need for volume estimates.—What is the composition of the effusive rocks in these regions? When we consider the relation between the origin of fault troughs and volcanism, it is certainly not the multiplicity of rock species that concerns us in the first place, though it is interesting from a petrographic point of view. What counts primarily is the bulk of the effusive rocks. Estimates of volume are rare, because petrologists are specialists who are more interested in rare rocks than in ordinary ones, and because the old-school petrography was essentially a science of the laboratory, which worked nearly exclusively with the polarizing microscope and chemical analysis. Fortunately, petrography has lately developed into petrology and is joining hands with its mother science, geology. The geological position and the volume of the igneous rocks brought to light in a given region are now being given special attention. Geology cannot draw conclusions without such data.

Local multiplicity of rock types.—For the purposes of this paper we need not dwell at length on the very remarkable multiplicity of rocks described by A. Holmes and H. F. Harwood (1937) from the Bufumbira region, part of Virunga north of Lake Kivu. For the major part they are basic rocks. C. Friedländer (1949) has assembled all analyses from the Kivu territory. The very acid rocks from Biega and Kahusi, examined by C. Sorotchinsky (1934), are effusive rocks that follow basalt flows and cover a very small surface compared with that of the basic rocks north and south of Lake Kivu. In the lava field north of Lake Kivu, according to the map of Friedländer, the area of basic lava is to that of acid lava as 240 to 1. South of Lake Kivu this proportion is as 17 to 1; but the volcanic region south of Lake Kivu reaches much farther than shown on Friedländer's map. According to G. Passau (1932) the volcanic region north of Lake Kivu covers 3200 square kilometers, that to the south 5500 kilometers. The acid rocks of Kahusi and Biega cover only an area of some tens of square kilometers.

C. Sorotchinsky (1934) has distinguished three volcanic phases in the building of the volcanoes Biega and Kahusi, caused by dislocations. The first phase is characterized by basaltic flows. The second has brought to the surface ultra-acid rhyolitic flows with a minimum of 80 per cent of silicon and relatively high potassium. The third phase has brought acid porphyries, rich in potassium.

The enrichment in alkali and the impoverishment in silicon from the second to the third phase Sorotchinsky explains by supposing that underlying rocks, rich in alkali, were assimilated. But it does not follow that Sorotchinsky assumes a primary basalt below the earth's crust. He thinks that the three magmas were generated by fusion of: amphibolite, then gneiss, and finally mica schist. A Holmes (Holmes and Harwood, 1937), in treating the rocks from Bufumbira, also explains the effusions of chemically different lavas by fusion of underlying rocks.

Basaltic parent magma and Earth's crust.—Nevertheless it seems reasonable to conceive, for the whole African fracture field, an underlying basaltic magma, which has fed the big outpouring of lava, and which has also, by assimilation of overlying rocks, given rise to a multitude of alkaline lavas. But then the question arises: What do we mean by the expression "underlying magma"? We know that the spherical layers below the earth's crust cannot be liquid, as transverse waves pass through them. A liquid magmatic layer does not exist. But we must assume under the earth's crust a layer where a "latent magmatic" state reigns. This state can change locally and temporarily into the liquid state—that is, into real magma. It still seems to me that this change is caused by diminution of the vertical pressure brought about by tectonic movements.

Here I have used the expression "earth's crust," which, without further definition, is too hazy, especially for the critical audience of a geophysical congress. As a geologist, I should like to place the lower limit of the earth's crust, not at the discontinuity of Mohorovičić, where the velocity of the longitudinal waves leaps from 6.9 to 8 kilometers per second, but rather deeper, where this velocity decreases from 8 to 7.9 km. per sec. According to Gutenberg (1948) this happens at a depth of about 80 km.

R. A. Daly (1933) has attributed this transition to a change of the crystalline state into the

vitreous state.[1] I think, for geologists, it is rational to call earth's crust that part of the outer shells of the earth that is crystalline; the underlying substratum is vitreous. This substratum, or "the mantle", reaches from 80 to 2900 km. of depth, where the earth's core begins, whose physical state and composition are not yet clearly known.

Returning to our principal topic, we observe that the lava flows on both sides of the Great East African fault trough are much greater in area and older than those within the graben. G. T. Prior (1903) and E. Krenkel (1910) mention basalts with plagioclase and olivine, nephelites with or without olivine, phonolites over a great extent, and trachytes, rhyolites, and comendites. It seems that here, too, the basic rocks are preponderant. To the north, in Ethiopia, we meet the same difficulties. Many species of basic and acid rocks are mentioned, but the evaluation of their volumes is lacking. Nevertheless, when we read Krenkel (1926) on the geology of what he calls "Abessomalien", we get an impression that the prevalent rocks are basic.

Effusive Rocks of Arabia and Syria

Concerning Arabia and Syria, M. Blanckenhorn (1914) gives some information; for Syria the work of L. Dubertret (1933) is more recent, and contains a beautiful geological map on the scale of 1:1,000,000. According to Blanckenhorn the young (Oligocene to Recent) effusive rocks are basalts. He writes: "It will be difficult to find another region with such strong volcanic activity, chiefly during the Pleistocene period, as in Arabia and Syria" (1914, p. 43). Dubertret (1933) states that in southern Syria the lava flows cover some 33,000 square kilometers. The most important mass of this extensive area is Djebel Druse. These volcanic rocks are basalts and dolerites. Here it seems quite certain that we have voluminous outpourings of basic rocks.

[1] Perhaps the transition from the crystalline state into the vitreous state takes place at a greater depth. B. Gutenberg and C. F. Richter (1939) write of a change in physical state at a depth of about 100 km. L. Mintrop (1949), discussing the results of the explosion in Heligoland of November 20, 1947, found a plastic zone between 110 and 118 km. of depth, where the velocity of the longitudinal waves falls from 9.2 to 7 km. per sec. and then rises to 11 km. per sec. below a depth of 118 km. This perhaps indicates that the thickness of the earth's crust would amount to 110 km.

Conclusion

The lava flows, which have been reviewed, came, in part, to the surface through faults that border the fault troughs, or through faults more or less parallel to those within the graben; others, however, lie at some distance from the fault troughs, *e.g.*, those in Kenya, Ethiopia, Arabia, and Syria. Nevertheless, their geographic distribution points to a certain relation between these basic lavas and the origin of the graben.

It seems to me that we can draw the following conclusion from this survey: The volcanism of the system of African fault troughs is a consequence of tensional forces in horizontal direction, which have opened the earth's crust in such a way that the basic vitreous substratum has changed from the latent magmatic state into fluid magma, which has reached the surface and formed basaltic lava flows. The multiplicity of effusive rocks in the graben would be the consequence of assimilation of pre-existing rocks in the graben. The big outpourings of basalts, outside the graben, represent the rise of basic magma along tension faults without vertical displacement, though, if this is true, the faults should be more or less vertical.

Perhaps it is permissible to add the following: It does not seem likely that magmatic differentiation has played an important role in the formation of igneous rocks in areas of tensional strain; it seems to belong to areas of compressional folding.

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Dorpsstraat 53. Oegstgeest, Holland
Manuscript Received by the Secretary of the Society, September 28, 1951

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 757–764 AUGUST 1952

AGE OF THE BEAR RIVER FORMATION, WYOMING

By Teng-Chien Yen

Abstract

The age of the Bear River formation is maintained to be Cenomanian. This age assignment is supported by the fossil content of the formation: (1) species of *Pyrgulifera*, a characteristic genus of the Bear River, have been recorded abundantly in different parts of Europe, and their known range is Upper Cretaceous (Cenomanian to Danian); (2) species of *Pyrgulifera* and at least 10 congeneric and closely similar species of the Bear River formation were found in the Gardonian formation in southern France, and the Gardonian is considered a standard representative of Upper Cenomanian; (3) the *Pyrgulifera*-bearing beds exposed elsewhere in Europe, which are considered to be younger than the Cenomanian, did not yield species closely similar and congeneric with those of the Bear River formation, despite their apparently similar habitat conditions; and (4) species of *Pyrgulifera* in North America have been found in the beds stratigraphically above the Bear River, but not below it.

CONTENTS

	Page		Page
Introduction	757	Faunal history	760
Acknowledgments	758	What is the age of the Bear River formation?	761
Characteristic species of *Pyrgulifera* Meek	758	References cited	762
Molluscan assemblages	760		

Introduction

After their discovery in 1859 by Henry Engelmann, the Bear River strata were for a score of years called "the Bear River estuary beds" and the "Bear River Laramie." These beds were at first considered Tertiary. Meek in 1873 expressed the first doubt about this age assignment and suggested that the beds might be Upper Cretaceous. Engelmann likewise in his final report of 1876 concluded that the Bear River strata were Cretaceous. For over 30 years no serious studies of these beds were attempted, and the age problem was left unsettled. As a result of his field investigation in 1891, T. W. Stanton, however, concluded that the Bear River beds occupy a much lower position than the Laramie beds, and he designated them the Bear River formation and assigned them to a level "near the base of the Upper Cretaceous."

Recently species of *Gastroplites* and *Neogastroplites* were collected from the Mowry shale in Montana and Wyoming, and these occurrences were used as evidence for shifting the age of the Mowry shale from Upper to Lower Cretaceous (Cobban and Reeside, 1951). The Mowry shale in Montana and northern Wyoming is considered equivalent to the lithologically similar Aspen shale in southwestern Wyoming, a correlation supported by the recognition of both *Gastroplites* and *Neogastroplites* in the Aspen. The Aspen overlies the Bear River formation. If this correlation on the basis of *Gastroplites* etc. be considered conclusive, the Bear River beds should be assigned to the Lower Cretaceous.

During the past 2 years, the writer has studied the nonmarine molluscan faunas of southwestern Wyoming. The Bear River strata constitute part of the sequence examined, and,

[1] This paper constitutes one of the contributions from a research project (NR-081-097) supported by the Geophysics Branch, Office of Naval Research, Department of the Navy. It is carried on under ONR Contract N9-ONR-92601 with Smithsonian Institution, Washington, D. C. It is published by permission of the Secretary of the Institution.

since their age has a significant bearing on problems of related beds in a neighboring area, an investigation of the age of the richly fossiliferous Bear River formation is deemed necessary.

In seeking to determine the age of the Bear River formation, we must first consider the evidence of its paleontological data. These are presented in three parts: (1) characteristic species of *Pyrgulifera* Meek; (2) molluscan assemblages; and (3) faunal history in the areas outside the type locality.

Acknowledgments

The author expresses his heart-felt thanks to John B. Reeside, Jr. and W. W. Rubey, both of U. S. Geological Survey, for their personal guidance in the field, when he worked in southwestern Wyoming in 1949 and 1950. He is also grateful to them for their critical reading of this manuscript; however, they may or may not agree with the conclusion in total or in part.

Characteristic Species of Pyrgulifera Meek

Mention of the Bear River formation immediately brings to mind its characteristic species of *Pyrgulifera*, a genus described by Meek in 1860, based on the very common species *humerosa*. As far as known, the genus in North America has been reported only from the Bear River and its partly contemporaneous strata in southwestern Wyoming, although a doubtful record, *Pyrgulifera meeki*, was reported from Fairburg, Nebraska, by White (1894). However, outside this continent, species have been assigned to *Pyrgulifera* with a longer range and wider distribution. The following 23 species have been described:

Pyrgulifera humerosa (Meek) (1860)
Pyrgulifera stantoni White (1895)
?*Pyrgulifera meeki* White (1894)
Pyrgulifera munieri (Repelin) (1902, pl. 6, fig. 37–40)
?*Pyrgulifera praecursor* (Sandberger) (1875-*Tanalia pilcheri* Fric, 1869, *non Hoernes*, pl-fig. 5)
?*Pyrgulifera* (?) *japonica* Matumoto (1938, fig. 23a, b)
Pyrgulifera pilcheri (Hoernes) (1857; Stoliczka, 1860, pl. 1, fig. 7–8)
?*Pyrgulifera pilcheri* var. *nassaeformis* (Sandberger) (1875, pl. 3, fig. 9, 9a)
Pyrgulifera spinosa (Sandberger) (1875, pl. 3, fig. 7. 7a)
?*Pyrgulifera acinosa* (Zekeli) (1852, pl. 9, fig. 7–10)
?*Pyrgulifera corrosa* Frech (1887, pl. 15, fig. 15–22)
Pyrgulifera ajkaensis Tausch (1885, pl. 2, fig. 8, 8a, 9)
Pyrgulifera riethmulleri Oppenheim (1892, pl. 34, fig. 2, 3)
Pyrgulifera rickeri Tausch (1885, pl. 2, fig. 6, 6a, 7)
Pyrgulifera hantkeni Oppenheim (1892, pl. 34, fig. 1, 1a)
?*Pyrgulifera striata* Tausch (1885, pl 2, fig. 5, 5a)
?*Pyrgulifera stomatopsidum* Stache (1889, pl. 5a, fig. 38)
?*Pyrgulifera neumayri* Holzapfel (1887, pl. 15, fig. 3, 4)
?*Pyrgulifera decheni* Holzapfel (1887, pl. 15, fig. 2)
?*Pyrgulifera gradata* (Rolle) (1858, pl. 2, fig. 13)
Pyrgulifera lyra (Matheron) (1842, pl. 37, fig. 8, 9)
Pyrgulifera armata (Matheron, 1842, pl. 37, fig. 12, 13)
?*Pyrgulifera matheroni* (Roule) (1884, pl. 5, fig. 4)

The genus was well described by Meek in 1877, and White (1895) quoted his description. Its important morphological features are thick shell substance, produced and turrited spire, angular and shouldered whorls, aperture faintly sinuous, but not notched or distinctly angular below. The sculpture is variable, but the intersecting spirals and ribs never become fimbriated or roundly nodulated.

The validity of the species listed above needs consideration. A query is prefixed to those names thought to be synonymous or of doubtful identification, and those based on single specimens. The other species, which are considered congeneric with *Pyrgulifera humerosa*, are given according to their range and distribution as follows:

(1) The Bear River formation, southwestern Wyoming: the age is subject to discussion in the present paper. The beds represent a series of alternating brackish-water and fresh-water deposits. Among other species of mollusks, it yields:

Pyrgulifera humerosa (Meek)—abundant

(2) The beds near Cokeville, Wyoming: these beds are partly contemporaneous with and partly younger than the Bear River beds. They consist mainly of fresh-water deposits, with brackish facies much less abundantly represented than in the Bear River formation, although not absent, and with some marine zones in the younger levels. In addition to some

unnamed varieties of *P. humerosa* and other molluscan species, these beds contain:

Pyrgulifera stantoni White—abundant

(3) The Gardonian beds in southern France: the age is Upper Cenomanian, according to Repelin (1902) and Pruvost (1942). They represent a series of brackish-water and fresh-water deposits. Among a rich assemblage of molluscan species in the beds of fresh-water origin, the following species was found:

Pyrgulifera munieri (Repelin)—common

(4) The Gosau beds of Brandenberg in North Tirol, Austria: the age is considered Cenomanian-Turonian by Sandberger (1875); Senonian by Schlosser (1895) and Kleblesberg (1935). They represent a series of marine and brackish-water deposits. The following species of *Pyrgulifera* were found in association with molluscan species of brackish-water habitat:

Pyrgulifera pilcheri (Hoernes)—abundant
Pyrgulifera spinosa (Sandberger)—common

(5) The Ajka beds in Bakony, western Hungary: the age is considered by Sandberger (1875) to be Cenomanian-Turonian; by Tausch (1886) and Oppenheim (1892) to be Upper Cretaceous (Turonian-Senonian). The beds are brackish-water and fresh-water deposits, underlain by a bed of marine limestone. In addition to a rich assemblage of molluscan species, they contain:

Pyrgulifera pilcheri (Hoernes)
Pyrgulifera hantkeni Oppenheim
Pyrgulifera rickeri Tausch
Pyrgulifera glabra (Hantken)
Pyrgulifera ajkaensis Tausch
Pyrgulifera riethmulleri Oppenheim

(6) The lignite beds in Les Martiques, Bouches des Rhone, France: the age is considered Senonian by Sandberger (1875) and Santonian (middle part of Senonian) by Repelin (1902). The beds are of brackish-water sedimentation. Among other species of gastropods, they contain:

Pyrgulifera lyra (Matheron)—common

(7) The lignite beds in Rognac, Bouches des Rhone, France: the age is considered Danian by Sandberger (1875) and Repelin (1902). They are fresh-water deposits. A rich assemblage of fresh-water and terrestrial species of gastropods includes:

Pyrgulifera armata (Matheron)—common

From these records of occurrences of *Pyrgulifera* in Europe, it is clear that all are assigned

TABLE 1.—EUROPEAN STAGES OF CRETACEOUS PERIOD

Britain		France	
Upper Cretaceous	Chalk	Upper	Danian Danian
			Senonian Maastrichtian Campanian Santonian Coniacian
			Turonian Turonian
			Cenomanian Cenomanian
	Upper Greensand and Gault	Middle	Albian Albian
Lower Cretaceous	Lower Greensand		Aptian Aptian
	Wealden beds	Lower	Neocomian Barremian Hauterivian Valendis

to the Upper Cretaceous, from Cenomanian to Danian. Moreover, the species of *Pyrgulifera* probably existed either in true fresh-water or in a brackish-fresh-water area, where an admixture of brackish- and fresh-water elements usually was found.

Molluscan Assemblages

The previous section indicates that the *Pyrgulifera*-bearing beds are probably of fresh-water origin, although some of the species were found in an admixture of brackish water and marine elements. Their habitat areas were probably close to an estuarian region where the water was likely to be brackish, and where an admixture with brackish-water or even marine faunas was too easily effected.

One of the important conditions for a more reliable conclusion from comparison of assemblages at different levels and in widely separated localities is that a close similarity in facies should be established if possible. Since the species of *Pyrgulifera*, which so far have been recorded in different localities, seem to indicate that they existed in closely similar kinds of habitats; therefore the presence of these gastropods in different localities may well be taken to mean that their enclosing deposits are probably similar in ecological facies.

After examining the data of all the *Pyrgulifera*-bearing beds, it is clear that the molluscan fauna of the Gardonian formation (representing the upper part of Cenomanian) is the most nearly comparable with that of the Bear River formation. The Gardonian beds have been well studied for over a century. From the beds of nonmarine origin, 35 species of aquatic gastropods are recorded, and 10 of them that closely resemble the Bear River species are listed here. Undoubtedly the similar species are congeneric, though the original nomenclature is retained for the species of the Gardonian beds.

Bear River beds	*Gardonian beds*
Corbula engelmanni	*Corbula zurcheri*
Corbicula durkeei	*Cyrena proboscidea*
Mesoneritina naticiformis	*Neritina primordialis*
Lioplax? endlichi	*Paludina dordonensis*
Valvata praecursoris	*Valvata arnaudi*
Pseudarinia convexa	*Physa subcylindrica*
Pyrgulifera humerosa	*Hantkenia munieri*
Pachychiloides chrysalis	*Potamides lignitarum*
Pachychiloides cleburni	*Tympanotomus vasseuri*
Physa usitata	*Physa symeyrolsensis*
Lymnaea nitidula	*Lymnaea conica*
Gyraulus sp. undet.	*Planorbis cretaceus*

On the other hand, six species of *Pyrgulifera* have been described from the Ajka beds in western Hungary, in association with a rich nonmarine molluscan fauna. Tausch (1886) has recorded over 50 species of gastropods and pelecypods, including species of several common fresh-water genera such as *Viviparus*, *Goniobasis*, *Hydrobia*, and *Ancylus*. However, no species in the Ajka fauna seems to resemble closely the congeneric species of the Bear River formation. This is also true of the other *Pyrgulifera*-bearing beds of post-Cenomanian age in Europe.

Faunal History

The Bear River formation in the type area is overlain by the marine Aspen shale and underlain by the nonfossiliferous light-colored nonmarine sandstones and clays of the upper part of the Beckwith formation. However, in the neighboring area toward the north, the underlying units include the Peterson and the Draney limestones of the Gannett group and an unnamed black shale on Smiths Fork near Cokeville. All these units are in places richly fossiliferous and of fresh-water origin. They are generally accepted as of Lower Cretaceous age.

Little has been published on the molluscan faunas of these older beds. On the basis of preliminary identifications of the available collections of Lower Cutaceous strata, the nearest comparable fauna is in the unnamed black shale on Smiths Fork, in which some Lower Cretaceous elements have been found in addition to the congeneric and closely resembling species of *"Corbicula"*, *Viviparus*, *Campeloma*, and *Lioplacodes*. These species are comparable with those of the Bear River beds and from which the Bear River fauna may be derived. However, no species of *Pyrgulifera* has been found in the black shale.

Moreover, congeneric species of *Campeloma*, *Lioplacodes*, *Mesoneritina*, *Mesocochliopa*, *Zaptychius*, *Physa*, and *Planorbis* have been found in the Lower Cretaceous strata as well as

in the Bear River formation, and the succession of the molluscan faunas in this general area is well illustrated by the presence of such rather rare genera as *Mesocochliopa* and *Zaptychius*. This continuity of faunistic distribution clearly indicates that the Bear River fauna is characteristic but not isolated and exotic.

The molluscan faunas of these beds are too incompletely known for us to determine their faunal relationships and to make definite comparisons for age determination. However, a recent contribution by Peck (1951) on nonmarine ostracodes from the same area provides evidence of a different group of invertebrates. By comparison between material from the Bear River strata and older beds, Peck concludes that the ostracod species of the Bear River are readily differentiated from those of the black shale on Smiths Fork, the Peterson and the Draney limestones, and the Cloverly formation.

What Is the Age of the Bear River Formation?

The Bear River strata have been assigned to a level near the base of the Upper Cretaceous, namely of Cenomanian age. This conclusion is here supported by the following paleontological evidences: (1) the known range of *Pyrgulifera* in Europe is Upper Cretaceous, namely from Cenomanian to Danian; (2) species of *Pyrgulifera* and at least 10 congeneric and closely similar species of fresh-water gastropods from the Bear River strata were found in the Gardonian beds in southern France; (3) the *Pyrgulifera*-bearing strata exposed elsewhere in Europe, which are considered to be younger than Cenomanian, did not yield species of mollusks closely similar and congeneric with those of the Bear River formation, despite their apparently similar habitat conditions; and (4) the species of *Pyrgulifera* here in North America have been found in the strata stratigraphically above the Bear River formation, but not below it.

Thus the Bear River formation in North America is probably close in age to that of the Gardonian formation in southern France, and they are within the Cenomanian. Several points may substantiate this age assignment.

First of all the reliability of intercontinental correlation on the basis of nonmarine mollusks must be once more evaluated. The question is often raised: how reliable are these fossil nonmarine mollusks? The answer, is that, as the products of nature, one group of organic beings is just as good as another. However, its applied value may be different, owing to the difference in degree of collecting, preservation and quantity of the specimens and the availability of the known records. No generalization on usefulness can be applied to one group or another, and no single group may claim a precise accuracy sometimes even on the basis of single record, single specimen, or fragment of impressions and problematical data. In the light of present-day geographic distribution, we know that nonmarine mollusks have a comparatively wide range and strong faculty for dispersion (Yen, 1947). In the light of facts revealed by geological history, we have no shortage of examples to demonstrate the stratigraphic value of the fossil nonmarine mollusks, though they are a group of as yet inadequately studied invertebrates.

The distances involved in the intercontinental correlations seem enormous for the spread of congeneric species of a homogeneous nonmarine stock, but the time of geological units taken into account was indeed also long. The distances of the distribution of *Pyrgulifera* are no more remarkable than those involved in the penecontemporaneous distribution of the nonmarine lamellibranchs in Late Paleozoic times: species of *Anthracomya* have been recorded from Britain to Minusinsk Basin, to Kuznetsk, and Tungus Basins in Siberia, and to Fukien Province in southeastern China (in the Hukou shale); species of *Carbonicola* from Britain to the Donetz Basin; species of *Palaeanodonta* from Norway to Siberia, Africa to Burma; species of *Palaeomutela* from Oka-Volga Basin to Tanganyika. Examples are also available of nonmarine gastropods in Mesozoic and Cenozoic times: species of *Campeloma* in the Kootenai formation of North America and the Wealden formation of Britain, Germany, and Spain; the polygyral species of *Australorbis* in the Bridger formation in North America, the Lutetian in Europe, and an Eocene bed in North China; species of *Orygoceras* and

Angulorbis (*-Idahoella*) in the Pliocene beds in North America and the Balkan States. Above all, *Lymnaea palustris* (Mueller), *Aplexa hypnorum* (Linné), *Cionella lubrica* (Mueller), *Pupilla muscorum* (Linné), and *Vallonia pulchella* (Mueller) are known to have holarctic distribution in late Pleistocene and Recent times. These examples are no mere coincidences. They constitute indeed the known facts leading to further perfection of our methods in correlation.

A conclusion based on quantitative occurrence of certain species or the presence of a number of congeneric species in the beds under correlation will be more reliable than those based on a single or a few specimens. Quantitative analysis will express more accuracy in morphological features, and more specimens will readily show the constant features of the species. The morphological features will in turn furnish observable guidance to determine the forms under consideration as monophyletic or polyphyletic.

Morphological resemblance can sometimes be superficial, particularly among the comparatively simple-featured gastropods, which may seem alike, but may belong to different genera. There are ways to distinguish them, of course, but collecting a large number of specimens, if possible, is perhaps the only means available to paleontologists in dealing with the fossil forms.

The species of *Pyrgulifera* seem to have been numerous wherever they have been found. This abundance of specimens has permitted a sound definition of the morphological features of the genus and of the species herein included, which in turn has indicated clearly that these species are probably monophyletic. Consequently, the presence of *Pyrgulifera* in association with a number of other genera, all with closely similar species in both the Bear River and the Gardonian formations, can be interpreted to mean that the two series of strata are close in age. On the evidence presented above, it seems very unlikely that the Bear River in Wyoming could be Lower Cretaceous, while the Gardonian formation is accepted as standard upper Cenomanian in Europe.

The range of fresh-water molluscan genera in time is indeed greatly variable as being known by the available records: most of the common genera have a long history, others may be limited to an epoch of time, and still others seem to be restricted only to a certain age. Such ranges in time are of course by no means fixed; however, any extension of the ranges beyond an acceptable limit on records will require new findings of accurately identified forms from a deposit of indisputable age.

True species of *Pyrgulifera* have been recorded from the Upper Cretaceous strata in different parts of Europe as well as from the lower part of the Upper Cretaceous in the Western Interior of North America. Therefore this range of *Pyrgulifera* should not be freely shifted to the Lower Cretaceous unless a true species of the genus has been found in a deposit of well-established Lower Cretaceous age. As far as the available data show, in the richly fossiliferous beds in Wyoming and Idaho, species of *Pyrgulifera* have not been found even in the black shale on Smiths Fork, which is close to, but stratigraphically lower than, the Bear River formation. Nor can we find a record of that genus in any one of the Lower Cretaceous strata in Europe. *Pyrgulifera* must remain as a characteristic genus of nonmarine mollusks in the Upper Cretaceous strata, and evidently it had a wide geographical distribution in the Cenomanian time. However, its species became extinct shortly after that time in North America, and they continued to survive through the Danian age in Europe.

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Manuscript Received by the Secretary of the Society, January 22, 1952

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 765-776, 4 FIGS. AUGUST 1952

TABLE FOR COMPUTING THICKNESS OF STRATA MEASURED IN A TRAVERSE OR ENCOUNTERED IN A BORE HOLE

BY HUGO MANDELBAUM AND JOHN T. SANFORD

ABSTRACT

The measurement of stratigraphic sections, whether by tape and compass or by plane-table traverse, frequently yields data which must be calculated in terms of true thicknesses of beds.

The general formula for the calculation of thickness contains four variables. Tables are presented which facilitate this calculation. The use of the tables is illustrated by examples covering both surface and subsurface problems.

CONTENTS

TEXT

	Page
Introduction	765
Derivation of formulas	766
General formula	766
Special formulas	767
Formula for plane-table traverse	772
Explanation of tables	772
Construction and form of tables	772
Examples in use of tables	773
Special cases	774
Application to subsurface data	775
Application to plane-table data	775
Summary of instructions for use of tables	775
References cited	776

ILLUSTRATIONS

Figure	Page
1.—Block diagram of an up-slope traverse A_1D across a dipping bed	766
2.—Traverse across a bed with a dip opposite the slant	772
3.—Traverse progressing stratigraphically downward across a bed dipping in the same direction as the slant	772
4.—Traverse progressing stratigraphically upward across a bed dipping in the same direction as the slant	772

TABLES

Table	Page
1.—Correlation factors for dip and slope	768
2.—Correction for azimuth	770
	Facing page
3.—Thickness of stratum	772

INTRODUCTION

The acquisition of geological data concerned with stratigraphic and structural studies frequently involves the solution of three-dimensional problems with as many as six variables. The numerous subsurface stratigraphic sections made available through the activities of the petroleum industry have focused attention on the need for more accurate descriptions of surface sections, the procurement of which ordinarily involves the mathematical treatment of the measurements made in the field.

Problems involving the measurement of two variables are readily solved by the use of a slide rule, by tables and charts such as the excellent compilation presented by Lahee (1941), or by the methods offered by Palmer (1928). These frequently suffice in the determination of thickness, depth, and true dip. Unfortunately, however, many of the more important and extensive surface exposures occur in rough country where the direction of the traverse and the method of the measurements are dictated more by considerations of the ease of traverse than by the factors needed for the simplest calculation of the geological data. The data are frequently collected by measurements up the slope of a hill with a traverse at any angle to the strike and a dip conforming to or opposite

from the slope of the hill (Fig. 1). The azimuth of the traverse with regard to the strike of the beds, the dip of the beds, the distance measured, and its slope as well as the thicknesses of the beds are all variables. If any one of them is to be obtained, the other four must be considered

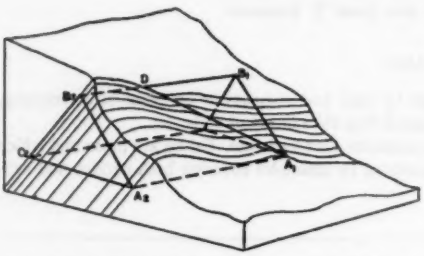

FIGURE 1.—BLOCK DIAGRAM OF AN UP-SLOPE TRAVERSE A_1D ACROSS A DIPPING BED

in the calculations. Occasionally it is advantageous to calculate the required data in the field so that sections may be plotted as aids in the collection of specimens or to permit comparison with other sections. In any event, they should be found before the notes become too "cold" if the most use is to be made of them. Calculation of a sufficient number of triangles to make all the corrections necessary on a section involving even a few hundred feet becomes extremely tedious and time consuming. To obviate this, a set of charts has been prepared by Mertie (1922). With these charts and a straight edge, any necessary corrections involving the thickness of or the depth to a stratum can be quickly obtained. The writers believe a compact set of tables would be more practical for field geologists and might have some advantage in accuracy for rapid work. Reference to a number of tables is no more time consuming than making the same number of readings from a chart, and the saving in bulk is considerable. Furthermore, the use of alignment charts requires a hard, plane working base for support, which is frequently not readily available, and the placing of the straight edge and the optical interpolation are sources of subjective errors. The use of the tables, which can easily be carried, would make it more feasible to reduce field notes to correct thicknesses when a section is being measured, and the notebook might be set up with a column for corrected thicknesses of strata.

The tables can also be used to determine true thicknesses of strata and depth in the subsurface when crooked holes and dipping formations are involved. Sufficient data for the solution of such a complex situation are seldom obtained, but, with the increased use of the dip meter and directional surveys, the problem may become more common.

DERIVATION OF FORMULAS

General Formula

Tables 1–3 are presented for the solution of general as well as special problems without any computations except the addition of two bidigital numbers.

The derivation of the general formula is a problem of solid geometry. The most general situation is a traverse s up a slope at an angle σ to the horizontal plane from a point A_1 at an outcrop to a point D at a higher outcrop (Figs. 2, 3). The slope of the traverse is called σ (sigma). The direction of the traverse s and the direction of the strike of the strata form an angle called the azimuth α of the traverse. In the figures, it is the angle between the projection A_1D' of s onto the horizontal plane ($A_1A_2C_2C_1$) and the direction of the strike $B_1'B_2'$ (Figs. 2, 3). Through A_1 and through D, horizontal lines A_1A_2 and B_1B_2 are drawn in the direction of the strike. Normals A_1B_1 and A_2B_2 between these two lines are called "slant line" s' of the outcrop between A_1 and D. The angle between a slant line s' and the horizontal plane is called the slant angle γ of the outcrop traversed. In the figures, it is the angle between A_2B_2 and A_2C_2.

Three situations with regard to the direction of the dip δ to that of the slant γ may be encountered:

Case I (Fig. 2), the dip has a direction opposite to that of the slant.

Case II (Fig. 3), the dip has the same direction as the slant and $\delta > \gamma$.

Case III (Fig. 4), the dip has the same direction as the slant and $\delta < \gamma$.

The dip δ appears in the figures between the lines B_2C_2 and the horizontal A_2C_2. The shaded area in the figures represents a section normal to the strike of the strata of which $A_2T = t$, the true thickness, has to be calculated. The following relationships can be read from the drawings (all letters bearing the subscript 1 are congruent to those bearing the subscript 2):

The projection of the traverse $A_1D = s$ onto the horizontal plane is expressed by the equation

$$A_1D' = s \cdot \cos \sigma \tag{1}$$

The projection of A_1D' onto the plane of the slant triangle $A_1B_1C_1$ is

$$A_1B_1' = A_1D' \cdot \sin \alpha$$

and because of (1)

$$A_1B_1' = s \cdot \cos \sigma \cdot \sin \alpha \tag{2}$$

The difference in elevation between the end points A_1 and D of the traverse s appears in the figures as

$$DD' = s \cdot \sin \sigma \tag{3}$$

The quantity B_2C_2 is the length of the bed measured in the direction of the dip between the upper outcrop and a horizontal plane through the lower outcrop. The projection of B_2C_2 onto the horizontal plane is

$$B_2'C_2 = B_2B_2' \cdot \cot \delta$$

Since $B_2'B_2 = DD' = s \cdot \sin \sigma$ (see (3)), the equation for $B_2'C_2$ can be written

$$B_2'C_2 = s \cdot \sin \sigma \cdot \cot \delta \tag{4}$$

For the horizontal distance A_2C_2 between the two surfaces of the strata, the following relationships exist:

In case I (Fig. 2) $A_2C_2 = A_2B_2' + B_2'C_2$ and because of (2) and (4)

$$A_2C_2 = s(\cos \sigma \cdot \sin \alpha + \sin \sigma \cdot \cot \delta) \tag{5}$$

In case II (Fig. 3) $A_2C_2 = A_2B_2' - B_2'C_2$ and because of (2) and (4)

$$A_2C_2 = s(\cos \sigma \cdot \sin \alpha - \sin \sigma \cdot \cot \delta) \tag{5'}$$

In case III (Fig. 4) $A_2C_2 = B_2'C_2 - A_2B_2'$ and because of (2) and (4)

$$A_2C_2 = s(\sin \sigma \cdot \cot \delta - \cos \sigma \cdot \sin \alpha) \tag{5''}$$

Finally the thickness of the stratum measured on a normal between the two surfaces of the strata may be expressed in the following equations:

$$A_2T = t = A_2C_2 \cdot \sin \delta$$

and because of (5), (5'), (5")

Case I $t = s(\sin \alpha \cdot \sin \delta \cdot \cos \sigma + \cos \delta \cdot \sin \sigma)$
Case II $t = s(\sin \alpha \cdot \sin \delta \cdot \cos \sigma - \cos \delta \cdot \sin \sigma)$
Case III $t = s(\cos \delta \cdot \sin \sigma - \sin \alpha \cdot \sin \delta \cdot \cos \sigma)$

or in a general formula

$$t = s\,|\sin \alpha \cdot \sin \delta \cdot \cos \sigma \pm \cos \delta \cdot \sin \sigma\,| \tag{6}$$

where the vertical bars indicate the absolute value of a possible difference.[1]

Special Formulas

This general formula (6) includes all special cases:

(a) If the section is measured on a lope but perpendicular to the strike, then

$$\alpha = 90°, \qquad \sin \alpha = 1$$

and

$$t = s\,|\sin \delta \cdot \cos \sigma \pm \cos \delta \cdot \sin \sigma)$$

(b) If the traverse is in a horizontal plane, than $\sigma = 0$ and with it $\sin \sigma = 0$ and $\cos \sigma = 1$, the formula (6) reduces to

$$t = s \cdot \sin \alpha \cdot \sin \delta$$

If the section is measured perpendicular to the strike, then

$$\alpha = 90°, \qquad \sin \alpha = 1$$

and

$$t = s \cdot \sin \delta$$

---

[1] J. B. Mertie, who developed this formula (1942) with the methods of descriptive geometry, neglected to distinguish between cases II and III and does, therefore, not indicate in his formula that the difference $\sin \alpha \cdot \sin \delta \cdot \cos \sigma - \cos \delta \cdot \sin \sigma$ might be negative (Case III) in which case the absolute value has to be taken.

Dip \ Slope	2°	4°	6°	8°	10°	12°	14°	16°	18°	20°	22°	24°	26°	28°	30°	32°	34°	36°	38°	40°	Dip \ Slope
0°	3.5	7.0	10	14	17	21	24	28	31	34	37	41	44	47	50	53	56	59	62	64	0°
6°	3.5	6.9	10	14	17	21	24	27	31	34	37	40	44	47	50	53	46	58	61	64	6°
10°	3.4	6.9	10	14	17	21	24	27	30	34	37	40	43	46	49	52	55	58	61	63	10°
12°	3.4	6.8	10	14	17	20	24	27	30	33	37	40	43	46	49	52	55	57	60	63	12°
14°	3.4	6.8	10	13	17	20	24	27	30	33	36	40	42	46	49	51	54	57	60	62	14°
16°	3.4	6.7	10	13	17	20	23	26	30	33	36	39	42	45	48	51	54	56	59	62	16°
18°	3.3	6.6	10	13	17	20	23	26	29	33	36	39	42	45	48	50	53	56	59	61	18°
20°	3.3	6.5	10	13	16	20	23	26	29	32	35	38	41	44	47	50	53	55	58	60	20°
22°	3.2	6.5	10	13	16	19	22	25	29	32	35	38	41	44	46	49	52	54	57	60	22°
24°	3.2	6.4	10	13	16	19	22	25	28	31	34	37	40	43	46	48	51	54	56	59	24°
26°	3.1	6.3	9.4	12	16	19	22	25	28	31	34	37	39	42	45	48	50	53	55	58	26°
28°	3.1	6.2	9.2	12	15	18	21	24	27	30	33	36	39	41	44	47	49	52	54	57	28°
30°	3.0	6.0	9.0	12	15	18	21	24	27	30	32	35	38	41	43	46	48	51	53	56	30°
32°	3.0	5.9	8.9	12	15	18	21	23	26	29	32	34	37	40	42	45	47	50	52	55	32°
34°	2.9	5.8	8.7	12	14	17	20	23	26	28	31	34	36	39	41	44	46	49	51	53	34°
36°	2.8	5.6	8.5	11	14	17	20	22	25	28	30	33	35	38	40	43	45	48	50	52	36°
38°	2.8	5.5	8.2	11	14	16	19	22	24	27	30	32	34	37	39	42	44	46	49	51	38°
40°	2.7	5.3	8.0	11	13	16	19	21	24	26	29	31	34	36	38	41	43	45	47	49	40°
42°	2.6	5.2	7.8	10	13	15	18	20	23	25	28	30	33	35	37	39	42	44	46	48	42°
44°	2.5	5.0	7.5	10	13	15	17	20	22	25	27	29	32	34	36	38	40	42	44	46	44°
46°	2.4	4.8	7.3	9.7	12	14	17	19	21	24	26	28	30	33	35	37	39	41	43	45	46°
48°	2.3	4.7	7.0	9.3	12	14	16	18	21	23	25	27	29	31	33	35	37	39	41	43	48°
50°	2.2	4.5	6.7	9.0	11	13	16	18	20	22	24	26	28	30	32	34	36	38	40	41	50°
52°	2.1	4.3	6.4	8.6	11	13	15	17	19	21	23	25	27	29	31	33	34	36	38	40	52°
54°	2.0	4.1	6.1	8.2	10	12	14	16	18	20	22	24	26	28	29	31	33	35	36	38	54°
56°	1.9	3.9	5.8	7.8	9.7	12	14	15	17	19	21	23	25	26	28	30	31	33	34	36	56°
58°	1.8	3.7	5.5	7.4	9.2	11	13	15	16	18	20	22	23	25	26	28	30	31	33	34	58°
60°	1.7	3.5	5.2	7.0	8.7	10	12	14	16	17	19	20	22	24	25	26	28	29	31	32	60°
62°	1.6	3.3	4.9	6.5	8.1	9.8	11	13	15	16	18	19	21	22	24	25	26	28	29	30	62°
64°	1.5	3.1	4.6	6.1	7.6	9.1	11	12	14	15	16	18	19	21	22	23	25	26	27	28	64°
66°	1.4	2.8	4.2	5.7	7.1	8.5	9.8	11	13	14	15	17	18	19	20	22	23	24	25	26	66°
68°	1.3	2.6	3.9	5.2	6.5	7.8	9.1	10	12	13	14	15	16	18	19	20	21	22	23	24	68°
70°	1.2	2.4	3.6	4.8	5.9	7.1	8.3	9.4	11	12	13	14	15	16	17	18	19	20	21	22	70°
72°	1.1	2.2	3.2	4.3	5.4	6.4	7.5	8.5	9.6	11	12	13	14	15	16	16	17	18	19	20	72°
74°	1.0	1.9	2.9	3.8	4.8	5.7	6.7	7.6	8.5	9.4	10	11	12	13	14	15	15	16	17	18	74°
76°	0.8	1.7	2.5	3.4	4.2	5.0	5.9	6.7	7.5	8.3	9.1	9.8	11	11	12	13	14	14	15	16	76°
78°	0.7	1.5	2.2	2.9	3.6	4.3	5.0	5.7	6.4	7.1	7.8	8.5	9.1	9.8	10	11	12	12	13	13	78°
80°	0.6	1.2	1.8	2.4	3.0	3.6	4.2	4.8	5.4	5.9	6.5	7.1	7.6	8.1	8.7	9.2	9.7	10	11	11	80°
82°	0.5	1.0	1.5	1.9	2.4	2.9	3.4	3.8	4.3	4.8	5.2	5.1	6.1	6.5	7.0	7.4	7.8	8.2	8.6	9.0	82°
84°	0.4	0.7	1.1	1.4	1.8	2.2	2.5	2.9	3.2	3.6	3.9	4.2	4.6	4.9	5.2	5.5	5.8	6.1	6.4	6.7	84°
86°	0.2	0.5	0.7	1.0	1.2	1.5	1.7	1.9	2.2	2.4	2.6	2.8	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.5	86°
88°	0.1	0.2	0.4	0.5	0.6	0.7	0.8	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	88°
	88°	86°	84°	82°	80°	78°	76°	74°	72°	70°	68°	66°	64°	62°	60°	58°	56°	54°	52°	50°	Dip \ Slope

Operation (A) Use top index for slope and left index for dip. Note this product P_1 on paper.
Operation (B) Use bottom index for slope and right index for dip. With this product P_2 proceed to Table 2.

Dip \ Slope	42°	44°	46°	48°	50°	52°	54°	56°	58°	60°	62°	64°	66°	68°	70°	72°	74°	76°	78°	80°	84°	90°	
0°	67	69	72	74	77	79	81	83	85	87	88	90	91	93	94	95	96	97	98	99	99	100	90°
6°	67	69	72	74	76	78	81	82	84	86	88	89	91	92	93	95	96	96	97	98	99	99	84°
10°	66	68	71	73	75	78	80	82	84	85	87	89	90	91	93	94	95	96	96	97	98	99	80°
12°	65	68	70	73	75	77	79	81	83	85	86	88	89	91	92	93	94	95	95	96	97	98	78°
14°	65	67	70	72	74	77	79	80	82	84	86	87	89	90	91	92	93	94	95	96	96	97	76°
16°	64	67	69	71	74	76	78	80	82	83	85	86	88	89	90	91	92	93	94	95	96	96	74°
18°	64	66	68	71	73	75	77	79	81	82	84	86	87	88	89	90	91	92	93	94	95	95	72°
20°	63	65	68	70	72	74	76	78	80	81	83	85	86	87	88	89	90	91	92	93	93	94	70°
22°	62	64	67	69	71	73	75	77	79	80	82	83	85	86	87	88	89	90	91	91	92	93	68°
24°	61	63	66	68	70	72	74	76	78	79	81	82	83	85	86	87	88	89	89	90	91	91	66°
26°	60	62	65	67	69	71	73	75	76	78	79	81	82	83	85	86	86	87	88	89	89	90	64°
28°	59	61	64	66	68	70	71	73	75	77	78	79	81	82	83	84	85	86	86	87	88	88	62°
30°	58	60	62	64	66	68	70	72	73	75	77	78	79	80	81	82	83	84	85	85	86	87	60°
32°	57	59	61	63	65	67	69	70	72	73	75	76	78	79	80	81	82	82	83	84	84	85	58°
34°	56	58	60	62	64	65	67	69	70	72	73	75	76	77	78	79	80	80	81	82	82	83	56°
36°	54	56	58	60	62	64	65	67	69	70	71	73	74	75	76	77	78	79	79	80	81	81	54°
38°	53	55	57	59	60	62	64	65	67	68	70	71	72	73	74	75	76	77	77	78	78	79	52°
40°	51	53	55	57	59	60	62	64	65	66	68	69	70	71	72	73	74	74	75	75	76	77	50°
42°	50	52	53	55	57	59	60	62	63	64	66	67	68	69	70	71	71	72	73	73	74	74	48°
44°	48	50	52	53	55	57	58	60	61	62	64	65	66	67	68	68	69	70	70	71	72	72	46°
46°	47	48	50	52	53	55	56	58	59	60	61	62	63	64	65	66	67	67	68	68	69	69	44°
48°	45	47	48	50	51	53	54	56	57	58	59	60	63	62	63	64	64	65	65	66	67	67	42°
50°	43	45	46	48	49	51	52	53	55	56	57	58	59	60	60	61	62	62	63	63	64	64	40°
52°	41	43	44	46	47	49	50	51	52	53	54	55	56	57	58	59	59	60	60	61	61	62	38°
54°	39	41	42	44	45	46	48	49	50	51	52	53	54	54	55	56	56	57	57	58	58	59	36°
56°	37	39	40	42	43	44	45	46	47	48	49	50	51	52	53	53	54	54	55	55	56	56	34°
58°	35	37	38	39	41	42	43	44	45	46	47	48	48	49	50	50	51	51	52	52	53	53	32°
60°	33	35	36	37	38	39	40	41	42	43	44	45	46	46	47	48	48	49	49	49	50	50	30°
62°	31	33	34	35	36	37	38	39	40	41	41	42	43	44	44	45	45	46	46	46	47	47	28°
64°	29	30	32	33	34	34	35	36	37	38	39	39	40	41	41	42	42	42	43	43	44	44	26°
66°	27	28	29	30	31	32	33	34	35	35	36	37	37	38	38	39	39	40	40	40	40	41	24°
68°	25	26	27	28	29	30	30	31	32	32	33	34	34	35	35	36	36	36	37	37	37	37	22°
70°	23	24	25	25	26	27	28	28	29	30	30	31	31	32	32	33	33	33	33	34	34	34	20°
72°	21	21	22	23	24	24	25	26	26	27	27	28	28	29	29	29	30	30	30	30	31	31	18°
74°	18	19	20	20	21	22	22	23	23	24	24	25	25	25	26	26	26	27	27	27	27	28	16°
76°	16	17	17	18	19	19	20	20	21	21	21	22	22	22	23	23	23	24	24	24	24	24	14°
78°	14	14	15	15	16	16	17	17	18	18	18	19	19	19	20	20	20	20	20	20	21	21	12°
80°	12	12	12	13	13	14	14	14	15	15	15	16	16	16	16	17	17	17	17	17	17	17	10°
82°	9.3	9.7	10	10	11	11	11	12	12	12	12	13	13	13	13	13	13	14	14	14	14	14	8°
84°	7.0	7.3	7.5	7.8	8.0	8.2	8.5	8.7	8.9	9.0	9.2	9.4	9.5	9.7	9.8	9.9	10	10	10	10	10	10	6°
86°	4.7	4.8	5.0	5.2	5.3	5.5	5.6	5.8	5.9	6.0	6.2	6.3	6.4	6.5	6.5	6.6	6.7	6.8	6.8	6.9	6.9	7.0	4°
88°	2.3	2.4	2.5	2.6	2.7	2.8	2.8	2.9	3.0	3.0	3.1	3.1	3.2	3.2	3.3	3.3	3.4	3.4	3.4	3.4	3.5	3.5	2°
Slope \ Dip	48°	46°	44°	42°	40°	38°	36°	34°	32°	30°	28°	26°	24°	22°	20°	18°	16°	14°	12°	10°	6°	0°	Dip \ Slope

Azimuth / P_2	2°	4°	6°	8°	10°	12°	14°	16°	18°	20°	22°	24°	26°	28°	30°	32°	34°	36°	38°	40°
10	.3	.7	1.0	1.4	1.7	2.1	2.4	2.8	3.1	3.4	3.7	4.1	4.4	4.7	5.0	5.3	5.6	5.9	6.2	6.4
12	.4	.8	1.3	1.7	2.0	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.3	5.6	6.0	6.4	6.7	7.1	7.4	7.7
14	.5	1.0	1.5	1.9	2.4	2.9	3.4	3.9	4.3	4.8	5.2	5.7	6.1	6.6	7.0	7.4	7.8	8.2	8.6	9.0
16	.6	1.1	1.7	2.2	2.8	3.3	3.9	4.4	4.9	5.5	6.0	6.5	7.0	7.5	8.0	8.5	8.9	9.4	9.9	10
18	.6	1.3	1.9	2.5	3.1	3.7	4.4	5.0	5.6	6.2	6.7	7.3	7.9	8.5	9.0	9.5	10	11	11	12
20	.7	1.4	2.1	2.8	3.5	4.2	4.8	5.5	6.2	6.8	7.5	8.1	8.8	9.4	10	11	11	12	12	12
22	.8	1.5	2.3	3.1	3.8	4.6	5.3	6.0	6.8	7.5	8.2	8.9	9.7	10	11	12	12	13	14	14
24	.8	1.7	2.5	3.3	4.2	5.0	5.8	6.6	7.4	8.2	9.0	9.8	11	11	12	13	13	14	15	15
26	.9	1.8	2.7	3.6	4.5	5.4	6.3	7.1	8.1	8.9	9.7	11	11	12	13	14	15	15	16	17
28	1.0	2.0	2.9	3.9	4.9	5.8	6.8	7.7	8.7	9.6	10	11	12	13	14	15	16	17	17	18
30	1.1	2.1	3.1	4.2	5.2	6.2	7.3	8.2	9.4	10	11	12	13	14	15	16	17	18	18	19
32	1.1	2.2	3.3	4.5	5.6	6.7	7.7	8.8	10	11	12	13	14	15	16	17	18	19	20	21
34	1.2	2.4	3.5	4.7	5.9	7.1	8.2	9.3	11	12	13	14	15	16	17	18	19	20	21	22
36	1.3	2.5	3.8	5.0	6.2	7.5	8.7	9.9	11	12	13	15	16	17	18	19	20	21	22	23
38	1.3	2.7	4.0	5.3	6.6	7.9	9.2	10	12	13	14	16	17	18	19	20	21	22	23	24
40	1.4	2.8	4.2	5.6	6.9	8.3	9.7	11	12	14	15	16	18	19	20	21	22	24	25	26
42	1.5	3.0	4.4	5.8	7.3	8.7	10	12	13	14	16	17	18	20	21	22	23	25	26	27
44	1.5	3.1	4.6	6.1	7.6	9.1	11	12	14	15	16	18	19	21	22	23	25	26	27	28
46	1.6	3.3	4.8	6.4	8.0	9.5	11	13	14	16	17	19	20	22	23	24	26	27	28	30
48	1.7	3.4	5.0	6.7	8.3	10	12	13	15	16	18	20	21	23	24	25	27	28	30	31
50	1.7	3.5	5.2	7.0	8.7	10	12	14	16	17	19	20	22	23	25	26	28	29	31	32
52	1.8	3.7	5.4	7.2	9.0	11	13	14	16	18	19	21	23	24	26	28	29	31	32	33
54	1.9	3.8	5.6	7.5	9.4	11	13	15	17	19	20	22	24	25	27	29	30	32	33	35
56	2.0	3.9	5.9	7.8	9.7	12	14	15	17	19	21	23	25	26	28	30	31	33	34	36
58	2.0	4.0	6.1	8.1	10	12	14	16	18	20	22	24	26	27	29	31	32	34	36	37
60	2.1	4.2	6.3	8.4	10	12	15	17	19	21	23	24	26	28	30	32	34	35	37	39
62	2.2	4.3	6.5	8.5	11	13	15	17	19	21	23	25	27	29	31	33	35	36	38	40
64	2.2	4.5	6.7	8.9	11	13	16	18	20	22	24	26	28	30	32	34	36	38	39	41
66	2.3	4.6	6.9	9.3	11	14	16	18	20	23	25	27	29	31	33	35	37	39	41	42
68	2.4	4.7	7.1	9.5	12	14	16	19	21	23	26	28	30	32	34	36	38	40	42	44
70	2.4	4.9	7.3	9.8	12	15	17	19	22	24	26	28	31	33	35	37	39	41	43	45
72	2.5	5.0	7.5	10	13	15	17	20	22	25	27	29	32	34	36	38	40	42	44	46
74	2.6	5.2	7.7	10	13	15	18	20	23	25	28	30	32	35	37	39	41	43	45	48
76	2.7	5.3	7.9	11	13	16	18	21	24	26	29	31	33	36	38	40	43	45	47	49
78	2.7	5.4	8.1	11	14	16	19	21	24	27	29	32	34	37	39	41	44	46	48	50
80	2.8	5.6	8.4	11	14	17	19	22	25	27	30	33	35	38	40	42	45	47	49	51
82	2.9	5.7	8.6	11	14	17	20	23	25	28	31	33	36	39	41	43	46	48	50	53
84	2.9	5.9	8.8	12	15	17	20	23	26	29	32	34	37	39	42	45	47	49	52	54
86	3.0	6.0	9.0	12	15	18	21	24	27	29	32	35	38	40	43	46	48	51	53	55
88	3.1	6.1	9.2	12	15	18	21	24	27	30	33	36	39	41	44	47	49	52	54	57
90	3.1	6.3	9.4	13	16	19	22	25	28	31	34	37	39	42	45	48	50	53	55	58
92	3.2	6.4	9.6	13	16	19	22	25	28	32	35	37	40	43	46	49	51	54	57	59
94	3.3	6.6	9.8	13	16	19	23	26	29	32	35	38	41	44	47	50	52	55	58	60
96	3.4	6.7	10	13	17	20	23	27	30	33	36	39	42	45	48	51	54	56	59	62
98	3.4	6.8	10	14	17	20	24	27	30	34	37	40	43	46	49	52	55	58	60	63
100	3.5	7.0	10	14	17	21	24	28	31	34	37	41	44	47	50	53	56	59	62	64
Azimuth	2°	4°	6°	8°	10°	12°	14°	16°	18°	20°	22°	24°	26°	28°	30°	32°	34°	36°	38°	40°

With the product P_2 of Table 1 proceed to the left index. Find the product P_3 for the given azimuth.
Add P_1 and P_3 for dip and slope in opposite direction.
Subtract P_1 from P_3, or P_3 from P_1 (whichever is larger) for dip and slope in same direction.
With the sum or difference D proceed to Table 3.

Azimuth / P_2	42°	44°	46°	48°	50°	52°	54°	56°	58°	60°	62°	64°	66°	68°	72°	76°	80°	84°	90°
10	6.7	6.9	7.2	7.4	7.7	7.9	8.1	8.3	8.5	8.7	8.8	9.0	9.1	9.3	9.5	9.7	9.8	9.9	10
12	8.0	8.3	8.6	8.9	9.2	9.5	9.7	9.9	10	10	11	11	11	11	11	12	12	12	12
14	9.4	9.7	10	10	11	11	11	12	12	12	12	13	13	13	13	14	14	14	14
16	11	11	12	12	12	13	13	13	14	14	14	14	15	15	15	16	16	16	16
18	12	13	13	13	14	14	15	15	15	16	16	16	16	17	17	17	18	18	18
20	13	14	14	15	15	16	16	17	17	17	18	18	18	19	19	19	20	20	20
22	15	15	16	16	17	17	18	18	19	19	20	20	20	20	21	21	22	22	22
24	16	17	17	18	18	19	19	20	20	21	21	22	22	22	23	23	24	24	24
26	17	18	19	19	20	21	21	22	22	23	23	23	24	24	25	25	26	26	26
28	19	19	20	21	21	22	23	23	24	24	25	25	26	26	27	27	28	28	28
30	20	21	21	22	23	24	24	25	25	26	27	27	28	28	29	29	30	30	30
32	21	22	23	24	25	25	26	27	27	28	28	29	30	30	30	31	32	32	32
34	23	24	24	25	26	27	27	28	29	29	30	31	32	32	32	33	34	34	34
36	24	25	26	27	28	28	29	30	31	31	32	32	33	33	34	35	36	36	36
38	25	26	27	28	29	30	31	31	32	33	34	34	35	35	36	37	37	38	38
40	27	28	29	30	31	32	32	33	34	35	35	36	37	37	38	39	39	40	40
42	28	29	30	31	32	33	34	35	36	36	37	38	38	39	40	41	41	42	42
44	29	31	32	33	34	35	36	37	37	38	39	40	40	41	42	43	43	44	44
46	31	32	33	34	35	36	37	38	39	40	41	41	42	43	44	45	45	46	46
48	32	33	35	36	37	38	39	40	41	42	42	43	44	45	46	47	47	48	48
50	33	35	36	37	38	39	40	41	42	43	44	45	46	46	48	49	49	50	50
52	35	36	37	39	40	41	42	43	44	45	46	47	47	48	49	51	51	52	52
54	36	37	39	40	41	43	44	45	46	47	48	49	49	50	51	52	53	54	54
56	37	39	40	42	43	44	45	46	48	49	49	50	51	52	53	54	55	56	56
58	39	40	42	43	44	46	47	48	49	50	51	52	53	54	55	56	57	58	58
60	40	42	43	45	46	47	49	50	51	52	53	54	55	56	57	58	59	60	60
62	41	43	45	46	48	49	50	51	53	54	55	56	56	57	59	60	61	62	62
64	43	45	46	48	49	50	52	53	54	55	57	58	58	59	61	62	63	64	64
66	44	46	47	49	51	52	53	55	56	57	58	59	60	61	63	64	65	66	66
68	46	47	49	51	52	54	55	56	58	59	60	61	62	63	65	66	67	68	68
70	47	49	50	52	54	55	57	58	59	61	62	63	64	65	67	68	69	70	70
72	48	50	52	54	55	57	58	60	61	62	64	65	66	67	69	70	71	72	72
74	50	51	53	55	57	58	60	61	63	64	65	66	67	69	70	72	73	74	74
76	51	53	55	56	58	60	61	63	64	66	67	68	69	70	72	74	75	76	76
78	52	54	56	58	60	62	63	65	66	67	69	70	71	72	74	76	77	78	78
80	54	56	58	59	61	63	65	66	68	69	71	72	73	74	76	78	79	80	80
82	55	57	59	61	63	65	66	68	69	71	72	74	75	76	78	80	81	82	82
84	56	58	60	62	64	66	68	70	71	73	74	75	76	78	80	82	83	84	84
86	58	60	61	64	66	68	70	71	73	74	76	77	78	80	82	83	85	86	86
88	59	61	63	65	67	69	71	73	75	76	78	79	80	82	84	85	87	88	88
90	60	62	65	67	69	71	73	75	76	78	79	81	82	83	86	87	89	89	90
92	62	64	66	68	71	72	74	76	78	80	81	83	84	85	88	89	91	91	92
94	63	65	68	70	72	74	76	78	80	81	83	84	86	87	89	91	93	93	94
96	64	67	69	71	74	76	78	80	81	83	85	86	87	89	91	93	95	95	96
98	66	68	70	73	75	77	79	81	83	85	87	88	89	91	93	95	97	97	98
100	67	69	72	74	77	79	81	83	85	87	88	90	91	93	95	97	98	99	100
Azimuth	42°	44°	46°	48°	50°	52°	54°	56°	58°	60°	62°	64°	66°	68°	72°	76°	80°	84°	90°

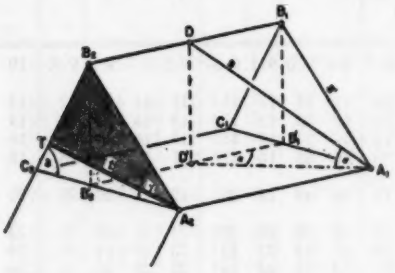

FIGURE 2.—TRAVERSE ACROSS A BED WITH A DIP OPPOSITE THE SLANT

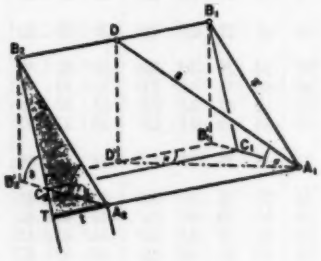

FIGURE 3.—TRAVERSE PROGRESSING STRATIGRAPHICALLY DOWNWARD ACROSS A BED DIPPING IN THE SAME DIRECTION AS THE SLANT

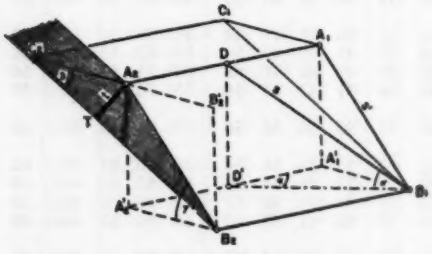

FIGURE 4.—TRAVERSE PROGRESSING STRATIGRAPHICALLY UPWARD ACROSS A BED DIPPING IN THE SAME DIRECTION AS THE SLANT

(c) If only the vertical distances are measured, then

$$\sigma = 90°, \quad \cos\sigma = 0, \quad \sin\sigma = 1$$

and

$$t = s \cdot \cos\delta$$

Formula for Plane-Table Traverse

If the data are recorded in terms of horizontal distance $d = A_1D'$ (Fig. 2) and difference in elevation $h = DD'$ as in plane-table mapping, then formula (6) can be changed to apply to these data. It is

$$d = s \cdot \cos\sigma$$

and

$$h = s \cdot \sin\sigma$$

Substituting these values in formula (6),

$$t = |\, d \cdot \sin\alpha \cdot \sin\delta \pm h \cdot \cos\delta \,| \tag{7}$$

where again the negative sign applies in case the dip has the same direction as the slant. This formula is given by Secrist (1941, p. 419) and applied to various problems by Nevin (1949, p. 352).

EXPLANATION OF TABLES

Construction and Form of Tables

In the general formula (6), the two products $\sin\delta \cdot \cos\sigma$ and $\cos\delta \cdot \sin\sigma$ are symmetrical expressions; they can, therefore, be tabulated in a single table (Table 1). Since the product $\sin\delta \cdot \cos\sigma$ assumes only values between 0 and

Table 3.—Thickness of Stratum

D \ S	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54
10	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6	3.8	4.0	4.2	4.4	4.6	4.8	5.0	5.2	5.4
12	1.4	1.7	1.9	2.2	2.4	2.6	2.9	3.1	3.4	3.6	3.8	4.1	4.3	4.6	4.8	5.0	5.3	5.5	5.8	6.0	6.2	6.5
14	1.7	2.0	2.2	2.5	2.8	3.1	3.4	3.6	3.9	4.2	4.5	4.8	5.0	5.3	5.6	5.9	6.2	6.4	6.7	7.0	7.3	7.6
16	1.9	2.2	2.6	2.9	3.2	3.5	3.8	4.2	4.5	4.8	5.1	5.4	5.8	6.1	6.4	6.7	7.0	7.4	7.7	8.0	8.3	8.6
18	2.2	2.5	2.9	3.2	3.6	4.0	4.3	4.7	5.0	5.4	5.8	6.1	6.5	6.8	7.2	7.6	7.9	8.3	8.6	9.0	9.4	9.7
20	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.0	8.4	8.8	9.2	9.6	10.0	10.4	10.8
22	2.6	3.1	3.5	4.0	4.4	4.8	5.3	5.7	6.2	6.6	7.0	7.5	7.9	8.4	8.8	9.2	9.7	10.1	10.6	11.0	11.4	11.9
24	2.9	3.4	3.8	4.3	4.8	5.3	5.8	6.2	6.7	7.2	7.7	8.2	8.6	9.1	9.6	10.1	10.6	11.0	11.5	12.0	12.5	13.0
26	3.1	3.6	4.2	4.7	5.2	5.7	6.2	6.8	7.3	7.8	8.3	8.8	9.4	9.9	10.4	10.9	11.4	12.0	12.5	13.0	13.5	14.0
28	3.4	3.9	4.5	5.0	5.6	6.2	6.7	7.3	7.8	8.4	9.0	9.5	10.1	10.6	11.2	11.8	12.3	12.9	13.4	14.0	14.6	15.1
30	3.6	4.2	4.8	5.4	6.0	6.6	7.2	7.8	8.4	9.0	9.6	10.2	10.8	11.4	12.0	12.6	13.2	13.9	14.4	15.0	15.6	16.2
32	3.8	4.5	5.1	5.8	6.4	7.0	7.7	8.3	9.0	9.6	10.2	10.9	11.5	12.2	12.8	13.4	14.1	14.7	15.4	16.0	16.6	17.3
34	4.1	4.8	5.4	6.1	6.8	7.5	8.2	8.8	9.5	10.2	10.9	11.6	12.2	12.9	13.6	14.3	15.0	15.6	16.3	17.0	17.7	18.4
36	4.3	5.0	5.8	6.5	7.2	7.9	8.6	9.4	10.1	10.8	11.5	12.2	13.0	13.7	14.4	15.1	15.8	16.6	17.3	18.0	18.7	19.4
38	4.6	5.3	6.1	6.8	7.6	8.4	9.1	9.9	10.6	11.4	12.2	12.9	13.7	14.4	15.2	16.0	16.7	17.5	18.2	19.0	19.8	21
40	4.8	5.6	6.4	7.2	8.0	8.8	9.6	10.4	11.2	12.0	12.8	13.6	14.4	15.2	16.0	16.8	17.6	18.4	19.2	20	21	22
42	5.0	5.9	6.7	7.6	8.4	9.2	10.1	10.9	11.8	12.6	13.4	14.3	15.1	16.0	16.8	17.6	18.5	19.3	20	21	22	23
44	5.3	6.2	7.0	7.9	8.8	9.7	10.6	11.4	12.3	13.2	14.1	15.0	15.8	16.7	17.6	18.5	19.4	20	21	22	23	24
46	5.5	6.4	7.4	8.3	9.2	10.1	11.0	12.0	12.9	13.8	14.7	15.6	16.6	17.5	18.4	19.3	20	21	22	23	24	25
48	5.8	6.7	7.7	8.6	9.6	10.6	11.5	12.5	13.4	14.4	15.4	16.3	17.3	18.2	19.2	20	21	22	23	24	25	26
50	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20	21	22	23	24	25	26	27
52	6.2	7.3	8.3	9.4	10.4	11.4	12.5	13.5	14.6	15.6	16.6	17.7	18.7	19.8	21	22	23	24	25	26	27	28
54	6.5	7.6	8.6	9.7	10.8	11.9	13.0	14.0	15.1	16.2	17.3	18.4	19.4	21	22	23	24	25	26	27	28	29
56	6.7	7.8	9.0	10.1	11.2	12.3	13.4	14.6	15.7	16.8	17.9	19.0	20	21	22	24	25	26	27	28	29	30
58	7.0	8.1	9.3	10.4	11.6	12.8	13.9	15.1	16.2	17.4	18.6	19.7	21	22	23	24	26	27	28	29	30	31
60	7.2	8.4	9.6	10.8	12.0	13.2	14.4	15.6	16.8	18.0	19.2	20	22	23	24	25	26	28	29	30	31	32
62	7.4	8.7	9.9	11.2	12.4	13.6	14.9	16.1	17.4	18.6	19.8	21	22	24	25	26	27	29	30	31	32	33
64	7.7	9.0	10.2	11.5	12.8	14.1	15.4	16.6	17.9	19.2	20	22	23	24	26	27	28	29	31	32	33	35
66	7.9	9.2	10.6	11.9	13.2	14.5	15.8	17.2	18.5	19.8	21	22	24	25	26	28	29	30	32	33	34	36
68	8.2	9.5	10.9	12.2	13.6	15.0	16.3	17.7	19.0	20	22	23	24	26	27	29	30	31	33	34	35	37
70	8.4	9.8	11.2	12.6	14.0	15.4	16.8	18.2	19.6	21	22	24	25	27	28	29	31	32	34	35	36	38
72	8.6	10.1	11.5	13.0	14.4	15.8	17.3	18.7	20	21	23	24	26	27	29	30	32	33	35	36	37	39
74	8.9	10.4	11.8	13.3	14.8	16.3	17.8	19.2	21	22	24	25	27	28	30	31	33	34	36	37	38	40
76	9.1	10.6	12.2	13.7	15.2	16.7	18.2	19.8	21	23	24	26	27	29	30	32	33	35	36	38	40	41
78	9.4	10.9	12.5	14.0	15.6	17.2	18.7	20	22	23	25	27	28	30	31	33	34	36	37	39	41	42
80	9.6	11.2	12.8	14.4	16.0	17.6	19.2	21	22	24	26	27	29	30	32	34	35	37	38	40	42	43
82	9.8	11.5	13.1	14.8	16.4	18.0	19.7	21	23	25	26	28	30	31	33	34	36	38	39	41	43	44
84	10.1	11.8	13.4	15.1	16.8	18.5	20	22	24	25	27	29	30	32	34	35	37	39	40	42	44	45
86	10.3	12.0	13.8	15.5	17.2	18.9	21	22	24	26	27	29	31	33	34	36	38	40	41	43	45	46
88	10.6	12.3	14.1	15.8	17.6	19.4	21	23	25	26	28	30	32	33	35	37	39	40	42	44	46	48
90	10.8	12.6	14.4	16.2	18.0	19.8	22	23	25	27	29	31	32	34	36	38	40	41	43	45	47	49
92	11.0	12.9	14.7	16.6	18.4	20	22	24	26	28	29	31	33	35	37	39	40	42	44	46	48	50
94	11.3	13.2	15.0	16.9	18.8	21	23	24	26	28	30	32	34	36	38	39	41	43	45	47	49	51
96	11.5	13.4	15.4	17.3	19.2	21	23	25	27	29	31	33	35	36	38	40	42	44	46	48	50	52
98	11.8	13.7	15.7	17.6	19.6	22	24	25	27	29	31	33	35	37	39	41	43	45	47	49	51	53
S	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54

D \ S	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98
10	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.0	7.2	7.4	7.6	7.8	8.0	8.2	8.4	8.6	8.8	9.0	9.2	9.4	9.6	9.8
12	6.7	7.0	7.2	7.4	7.7	7.9	8.2	8.4	8.6	8.9	9.1	9.4	9.6	9.8	10.1	10.3	10.6	10.8	11.0	11.3	11.5	11.8
14	7.8	8.1	8.4	8.7	9.0	9.2	9.5	9.8	10.1	10.4	10.6	10.9	11.2	11.5	11.8	12.0	12.3	12.6	12.9	13.2	13.4	13.7
16	9.0	9.3	9.6	9.9	10.2	10.6	10.9	11.2	11.5	11.8	12.2	12.5	12.8	13.1	13.4	13.8	14.1	14.4	14.7	15.0	15.4	15.7
18	10.1	10.4	10.8	11.2	11.5	11.9	12.2	12.6	13.0	13.3	13.7	14.0	14.4	14.8	15.1	15.5	15.8	16.2	16.6	16.9	17.3	17.6
20	11.2	11.6	12.0	12.4	12.8	13.2	13.6	14.0	14.4	14.8	15.2	15.6	16.0	16.4	16.8	17.2	17.6	18.0	18.4	18.8	19.2	19.6
22	12.3	12.8	13.2	13.6	14.1	14.5	15.0	15.4	15.8	16.3	16.7	17.2	17.6	18.0	18.5	18.9	19.4	19.8	20	21	21	22
24	13.4	13.9	14.4	14.9	15.4	15.8	16.3	16.8	17.3	17.8	18.2	18.7	19.2	19.7	20	21	21	22	22	23	23	24
26	14.6	15.1	15.6	16.1	16.6	17.2	17.7	18.2	18.7	19.2	19.8	20	21	21	22	22	23	23	24	24	25	25
28	15.7	16.2	16.8	17.4	17.9	18.5	19.0	19.6	20	21	21	22	22	23	24	24	25	25	26	26	27	27
30	16.8	17.4	18.0	18.6	19.2	19.8	20	21	21	22	23	23	24	25	25	26	26	27	28	28	29	29
32	17.9	18.6	19.2	19.8	20	21	22	22	23	24	24	25	26	26	27	27	28	29	29	30	31	31
34	19.0	19.7	20	21	22	22	23	24	24	25	26	27	27	28	29	29	30	31	31	32	33	33
36	20	21	22	22	23	24	24	25	26	27	27	28	29	30	30	31	32	32	33	34	35	35
38	21	22	23	24	24	25	26	27	27	28	29	30	30	31	32	33	33	34	35	36	36	37
40	22	23	24	25	26	26	27	28	29	30	30	31	32	33	34	34	35	36	37	38	38	39
42	24	24	25	26	27	28	29	29	30	31	32	33	34	34	35	36	37	38	39	39	40	41
44	25	26	26	27	28	29	30	31	32	33	33	34	35	36	37	38	39	40	40	41	42	43
46	26	27	28	29	29	30	31	32	33	34	35	36	37	38	39	40	40	41	42	43	44	45
48	27	28	29	30	31	32	33	34	35	36	36	37	38	39	40	41	42	43	44	45	46	47
50	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
52	29	30	31	32	33	34	35	36	37	38	40	41	42	43	44	45	46	47	48	49	50	51
54	30	31	32	33	35	36	37	38	39	40	41	42	43	44	45	46	48	49	50	51	52	53
56	31	32	34	35	36	37	38	39	40	41	43	44	45	46	47	48	49	50	52	53	54	55
58	32	34	35	36	37	38	39	41	42	43	44	45	46	48	49	50	51	52	53	55	56	57
60	34	35	36	37	38	40	41	42	43	44	46	47	48	49	50	52	53	54	55	56	58	59
62	35	36	37	38	40	41	42	43	45	46	47	48	50	51	52	53	55	56	57	58	60	61
64	36	37	38	40	41	42	44	45	46	47	49	50	51	52	54	55	46	58	59	60	61	63
66	37	38	40	41	42	44	45	46	48	49	50	51	53	54	55	57	58	59	61	62	63	65
68	38	39	41	42	44	45	46	48	49	50	52	53	54	56	57	58	60	61	63	64	65	67
70	39	41	42	43	45	46	48	49	50	52	53	55	56	57	59	60	62	63	64	66	67	69
72	40	42	43	45	46	48	49	50	52	53	55	56	58	59	60	62	63	65	66	68	69	71
74	41	43	44	46	47	49	50	52	53	55	56	58	59	61	62	64	65	67	68	70	71	73
76	43	44	46	47	49	50	52	53	55	56	58	59	61	62	64	65	67	68	70	71	73	74
78	44	45	47	48	50	51	53	55	56	58	59	61	62	64	66	67	69	70	72	73	75	76
80	45	46	48	50	51	53	54	56	58	59	61	62	64	66	67	69	70	72	74	75	77	78
82	46	48	49	51	52	54	56	57	59	61	62	64	66	67	69	71	72	74	75	77	79	80
84	47	49	50	52	54	55	57	59	60	62	64	66	67	69	71	72	74	75	77	79	81	82
86	48	50	52	53	55	57	58	60	62	64	65	67	69	71	72	74	76	77	79	81	83	84
88	49	51	53	55	56	58	60	62	63	65	67	69	70	72	74	76	77	79	81	83	84	86
90	50	52	54	56	58	59	61	63	65	67	68	70	72	74	75	77	79	81	83	85	86	88
92	52	53	55	57	59	61	63	64	66	68	70	72	74	75	77	79	81	83	85	86	88	90
94	53	55	56	58	60	62	64	66	68	70	71	73	75	77	79	81	83	85	86	88	90	92
96	54	56	58	60	61	63	65	67	69	71	73	75	77	79	81	83	84	86	88	90	92	94
98	55	57	59	61	63	65	67	69	71	73	74	76	78	80	82	84	86	88	90	92	94	96
S	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98

With the traverse s, measured in the field, proceed to the top index.
With the value D from Table 2 proceed to the side index. Find the thickness of the stratum.

1, the multiplication by $\sin \alpha$ can be arranged in a second table (Table 2). In case I the value of $\cos \delta \cdot \sin \sigma$ from Table 1 has to be added to the value of $\sin \delta \cdot \cos \sigma \cdot \sin \alpha$ from Table 2; in cases II and III the difference between the two values has to be found. This gives the factor by which the traverse s has to be multiplied to find the thickness t of the strata. Since this factor again is restricted to values between 0 and 1, the multiplication can also be arranged in a table (Table 3). Angular measurements with the usual geological field methods are reliable at best within the limits of $\pm\frac{1}{2}°$, measurements of distances in feet or paces within the limits of $\pm 1\%$. The irregularities of the surfaces and thicknesses of beds represent a further limitation to the accuracy of measurements. Products of two values that are not more reliable than these limits cannot be relied upon to be correct to more than two significant digits. Without limiting the correctness of the final result, the values in all tables need therefore be given in two significant digits only. This facilitates the arrangement and the interpolation for values not directly given in the tables.

Examples in Use of Tables

Table 1 contains the products $\cos \delta \cdot \sin \sigma$ and $\sin \delta \cdot \cos \sigma$ which are found by two operations—A and B.

OPERATION A: To find the product $\cos \delta \cdot \sin \sigma$, locate the value of the dip δ in the *left* vertical column and the value of the slope σ in the *top* horizontal row. The product $\cos \delta \cdot \sin \sigma$ is found at the intersection of the two.

Example 1. dip = 34°, slope = 26°
At the intersection of the horizontal row, marked at the left column as dip 34°, with the vertical column, marked at the top row as slope 26°, find 36. These are the two significant digits of the product $\cos 34° \cdot \sin 26°$ which, of course, is a number < 1—namely .36. The decimal points are omitted in the tables to improve the clarity.

OPERATION B: To find the product $\sin \delta \cdot \cos \sigma$, locate the values of δ in the *right* vertical column and the value of σ in the *bottom* horizontal row. Thus we find at the intersection of the 34° horizontal row and the 26° vertical column the number 50, which represents the two significant digits of the product $\sin 34° \cdot \cos 26°$.

Since only even numbers of degrees are listed for the dip and the slope, the product of functions of odd angles has to be interpolated in the usual manner. If both angles are odd, proceed as in the following example.

Example 2. Both angles are odd:
dip = 35°, slope = 27°
The product $\sin 35° \cdot \cos 27°$ (Operation A) is found between two numbers in a diagonal—namely
between $\cos 34° \cdot \sin 26° = .36$
and $\cos 36° \cdot \sin 28° = .38$
therefore $\cos 35° \cdot \sin 27° = .37$

The product $\cos \delta \cdot \sin \sigma$ (found in Operation A) will be designated P_1, and the product $\sin \delta \cdot \cos \sigma$ (found in Operation B) P_2. Table 2 contains the products $P_2 \cdot \sin \alpha$ which is called P_3. The quantity P_2 is tabulated in the left column, the azimuth α in the top row. The product $P_3 = P_2 \cdot \sin \alpha$ is then found at the intersection of the respective row and column.

Example 3. dip = 34°, slope = 26°, azimuth = 64°

From Table 1 (Operation B) we have $P_2 = 50$. In Table 2 from the value $P_2 = 50$ and the azimuth $\alpha = 64°$ a product $P_3 = 45$ is found. The quantity P_3 represents, without decimal point, the two significant digits of the product $P_2 \cdot \sin \alpha = (\sin 34° \cdot \cos 26°) \cdot \sin 64° = .45$ Interpolation for odd numbers P_2 and/or odd degrees of the azimuth α are carried out in the same manner as explained for Table 1. Numbers $P_2 < 10$ are not directly listed in Table 2. Products containing such factors can be found in the corresponding row of $10 \times P_2$ as follows:

Example 4. dip = 10°, slope = 80°, azimuth = 64°
From Table 1 (Operation B) $P_2 = 3.0$
Find in Table 2 the product $30 \times \sin 64°$ which is 27.
Divide this value by 10 to find $P_3 = 3.0 \times \sin 64° = 2.7$

After having found P_1 (Table 1, Operation A) and P_3 (Table 2), the sum $P_1 + P_3$ (case I) or the difference $|P_1 - P_3|$ (cases II

and III) has to be calculated. This sum or difference, which we call D, is the factor by which the length of the traverse s has to be multiplied to find the true thickness t of the stratum (*See* formula (6).) This multiplication is carried out with the aid of Table 3. In the left index column are tabulated values of D, in the top row those of the traverse s, for two significant digits. The product t is again given to two significant digits, except for values between 10 and 20 where three significant digits are justifiable. Interpolation for odd-numbered values of s and/or D are carried out in the manner explained for Table 1. Products containing for s and D numbers <10 are found in rows and/or columns marked with a value 10 times as large.

Example 5. Traverse $s = 45$ feet, dip $= 33°$, slope $= 26°$, azimuth $= 67°$ (dip in a direction opposite to the slant)

Table 1, Operation A $P_1 = 37$
Operation B $P_2 = 49$
Table 2 $P_2 = 49$, $\alpha = 67°$ $P_3 = 46$
$P_1 + P_3$ $D = 83$
Table 3 $D = 83$, $s = 45$ $t = 38$ ft.

As a result of the arrangement of the three tables, D is given with two significant digits as hundredths of a unit. The decimal place in the final answer has to be found accordingly by inspection.

Example 6. $D = 42$, $s = 21$ feet, $t = 8.8$ feet

Since Table 3 gives values of t between 10 and 20 to three significant digits, for numbers of this order of magnitude an accuracy of half a digit more is warranted.

Example 7. $D = 48$, $s = 28$ feet, $t = 13.4$ feet

The value of t ($t = 13.4$) is rounded off to the nearest half digit (13.5) rather than to the nearest full digit (13.0). In the following, a few more examples are fully carried out:

Example 8. Traverse $s = 125$ feet, dip $= 37°$, slope $= 12°$, azimuth $55°$ (dip in a direction opposite to the slant)

Table 1, Operation A $P_1 = 17$
Operation B $P_2 = 59$
Table 2 $P_2 = 59$, $\alpha = 55°$ $P_3 = 49$
$P_1 + P_3 =$ $D = 66$
Table 3 $D = 66$, $s = 125$ $t = 83$ ft.

Example 9. Traverse $s = 370$ feet, dip $= 45°$, slope $= 28°$, azimuth $= 72°$ (dip in the same direction as the slant)

Table 1, Operation A $P_1 = 34$
Operation B $P_2 = 62$
Table 2 $P_2 = 62$, $\alpha = 72°$ $P_3 = 59$
$P_2 - P_1 =$ $D = 25$
Table 3 $D = 25$, $s = 370$ $t = 92$ ft.

Special Cases

The tables can also be used for the three special cases previously mentioned.

(a) The traverse is perpendicular to the strike. In this case $\sin \alpha = 1$ and consequently $P_2 = P_3$. By adding or subtracting P_1 and P_3, D is found without use of Table 2.

Example 10. Traverse $s = 65$ feet, dip $= 7°$, slope $= 22°$ (dip opposite to slant)

Table 1, Operation A $P_1 = 37$
Operation B $P_2 = 11$
$P_1 + P_2 =$ $D = 48$
Table 3 $D = 48$, $s = 65$ $t = 32$ ft.

(b) The traverse is in a horizontal plane. In this case $\sin \sigma = 0$, and $\cos \sigma = 1$. Table 1, Operation A produces 0. Operation B consists of finding $\sin \delta$ in the last right column of Table 1, marked at the bottom with slope 0. With this value for P_2 proceed to Table 2, and from there directly to Table 3.

Example 11. Traverse $s = 470$ feet, dip $= 17°$ azimuth $= 34°$

Table 1, Operation B, right column $P_2 = 30$
Table 2 $P_2 = 30$, $\alpha = 34°$ $P_3 = 17$
Table 3 $P_3 = D = 17$, $s = 470$ $t = 80$ ft.

(c) Only vertical distances are measured. In this case $t = s \cdot \cos \delta$. Find $\cos \delta$ in Table 1, Operation A, in the last right column, using the left index column which starts with 0° at the top. With this

value P_1 proceed directly to Table 3 to find t.

Example 12. Height $s = 85$ feet, dip $= 75°$
Table 1, Operation A
(right column) $P_1 = 26$
Table 3 $P_1 = D = 26$,
$s = 85$ $t = 22$ ft.

Application to Subsurface Data

The table can also be used for calculating the true thickness of strata encountered in a borehole. In the simplest case—if the hole is vertical (or deviating only a few degrees from the vertical with dips of strata not extremely steep)—the thickness t of the stratum is found in the same way as in Example 12.

Example 13. Measured thickness $s = 18$ feet
dip $= 24°$
Table 1, Operation A (right column)
$P_1 = 91$
Table 3 $P_1 = D = 91$,
$s = 18$ $t = 16.5$ ft.

If the borehole is deviating considerably from the perpendicular and the inclination of the hole σ and the direction α of the slope relative to the strike of the strata are known, the true thickness of the stratum is found with the help of the tables in the same way as in Examples 5 to 9.

Example 14. Measured thickness $s = 40$ feet, Slope of hole $\sigma = 83°$ (The slope angle used here is the complement of the angle of deviation from the vertical.) Azimuth of hole relative to strike $\alpha = 25°$ Dip of stratum $\delta = 17°$ (same direction as σ).
Table 1, Operation A $P_1 = 95$
Operation B $P_2 = 3.5$
Table 2 $P_2 = 3.5$,
$\alpha = 25°$ $P_3 = 1.5$
$P_1 - P_3 =$ $D = 93$
Table 3 $D = 93$,
$s = 40$ $t = 38$ ft.

Application to Plane-Table Data[2]

The tables can be used also if the data are recorded in terms of horizontal distance d and difference in elevation h as in plane-table mapping, when formula (7) $t = |\alpha \cdot \sin \alpha \cdot \sin \delta \pm h \cdot \cos \delta|$ is applicable. To find the product $P_1 = h \cdot \cos \delta$, find $\cos \delta$ in the last column of Table 1 marked 90° on top (use left index) and proceed with this value D_1 as D and with h as s immediately to Table 3.

Example 15. $h = 36$ ft. dip $= 34°$

Locate the dip $\delta = 34°$ in the left index column (Table 1) and find in the last column (marked on top 90°) 83. Proceed with this value as D to Table 3 and find in the column marked 36 at the top the product $P_1 = h \cdot \cos \delta = 30$

To find the product $d \cdot \sin \alpha \cdot \sin \delta$, find $\sin \delta$ in the last column of Table 1, marked 90° on top, using the right index, and proceed with this value as P_2 to Table 2. Find there $P_2 \cdot \sin \alpha$ as in all previous examples. Proceed with this product D_2 as D and with the horizontal distance d as s to Table 3 to find $P_3 = d \cdot \sin \alpha \cdot \sin \delta$. Add P_1 and P_3 if the dip is opposite to the slope, calculate the difference between P_1 and P_3 if the dip is in the same direction as the slope. Note that since P_1 and P_3 have already been processed through Table 3 their sum or difference represents the final value for the thickness t in feet.

Example 16. $d = 240$ ft. $h = 36$ ft.
dip $= 34°$, azimuth $= 54°$
Table 1, Operation A (explained in Example 15)
$P_1 = 30$
Operation B: Locate the dip $\delta = 34°$ in the right index column (Table 1) and find in the last column (marked 90° on top)
$P_2 = 56$
Table 2, $P_2 = 56$,
$\alpha = 54°$ $D_2 = 45$
Table 3, $D_2 = 45$,
$s = d = 240$ $P_3 = 108$
if dip is opposite slope
$t = P_1 + P_3 =$ 138 ft.
if dip is same direction as slope
$t = |P_1 - P_3|$ 78 ft.

SUMMARY OF INSTRUCTIONS FOR THE USE OF TABLES

(A) Surface Strata

(1) Traverse s is perpendicular to strike Find P_1 and P_2 in Table 1.

[2] The authors are grateful to Professor Charles Nevin, who read the manuscript, for suggesting this application of the tables.

Find $D = P_1 + P_2$ for dip opposite to slant
or $D = |P_1 - P_2|$ for dip same as slant.
Find t in Table 3.
(*See* Example 10)

(2) Traverse s oblique to strike but in a horizontal plane.
Find $\sin \delta = P_2$ in the last column of Table 1 (marked at bottom 0°) using right index.
Find P_3 in Table 2.
Find t for $D = P_3$ in Table 3.
(*See* Example 11)

(3) Vertical distances are measured
Find $\cos \delta = P_1$ in the last column of Table 1 using left index.
Find t for $D = P_1$ in Table 3.
(*See* Example 12)

(4) Traverse s oblique to strike up a slope
Find P_1 and P_2 in Table 1.
Find P_3 for P_2 in Table 2.
Find $D = P_1 + P_3$ (for dip opposite to slant)
or $D = |P_1 - P_3|$ (for dip same as slant)
Find t in Table 3.
(*See* Examples 5 to 9)

(5) Plane-table traverse.
Find $D_1 = \cos \delta$ in last column Table 1 (use left index).
Find P_1 for $D_1 = D$ and $s = h$ (*See* Example 15).
Find $P_2 = \sin \delta$ in last column Table 1 (use right index).
Find D_2 for P_2 and α in Table 2.
Find P_3 in Table 3 for $D_3 = D$ and $s = d$.
Find $t = P_1 + P_3$ (for dip opposite to slant)
or $t = |P_1 - P_3|$ (for dip same as slant). (*See* Example 16)

(B) Subsurface Strata

(1) Bore hole nearly vertical and dips of strata not steep
Proceed as A3.
(*See* Example 13)

(2) Bore hole deviating from perpendicular
Proceed as A4.
(*See* Example 14)

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Palmer, Harold S. (1928) *New graphic method for determining the depth and thickness of strata and the projection of true dip*, U. S. Geol. Survey, Prof. Paper 120-G, p. 122–128, Pls. XIV–XVI.

Wayne University, Detroit, Mich.

Manuscript Received by the Secretary of the Society, May 28, 1951.

n Table 1

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SEISMIC REFRACTION PROFILES FROM ATLANTIS 164-CARYN 17 AND ATLANTIS 172-CARYN 22 CRUISES

LEGEND

- A164-C17 REVERSED PROFILE
- A164-C17 UNREVERSED PROFILE
- A172-C22 REVERSED PROFILE
- A172-C22 UNREVERSED PROFILE
- 1000 FATHOM CONTOUR

UNITED STATES

NEWFOUNDLAND

NOVA SCOTIA

FLORIDA

CUBA

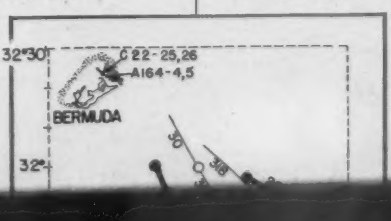
HISPANIOLA

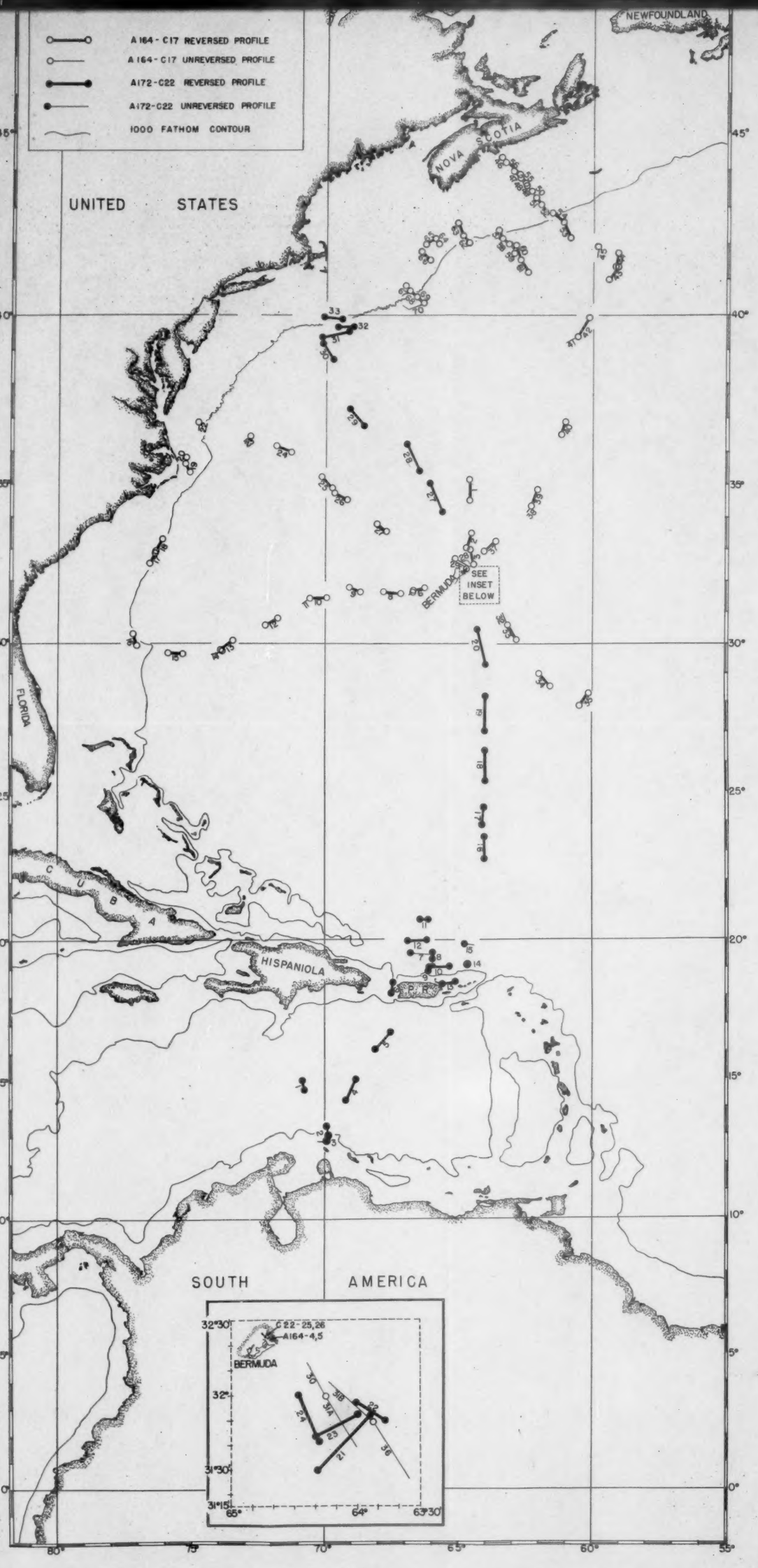
P. R.

BERMUDA

SEE INSET BELOW

SOUTH AMERICA





LOCATION OF REFRACTION PROFILES IN THE NORTH ATLANTIC

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 777-808, 22 FIGS., 4 PLS. AUGUST 1952

SEISMIC REFRACTION MEASUREMENTS IN THE ATLANTIC OCEAN. PART IV: BERMUDA, BERMUDA RISE, AND NARES BASIN

By Charles B. Officer, Maurice Ewing, and Paul C. Wuenschel

Abstract

This report describes the results of a series of refraction profiles made in the vicinity of the Bermuda Islands and along two lines of traverse extending south and southeast of Bermuda to the northern perimeter of the Nares Basin. On the profiles made near the Nares Basin four seismic layers were determined—an unconsolidated sediment with average velocity of 1.70 km/sec, consolidated volcanics and/or sediments with average velocity of 4.51 km/sec, a basement with average velocity of 6.63 km/sec, and a second basement with average velocity of 8.03 km/sec. The boundary between the two basements corresponds with the Mohorovicic discontinuity and is at an average depth of 10 km; the material above the Mohorovicic discontinuity corresponds in velocity with the intermediate layer of continental seismology. Over the Bermuda Rise only one high velocity basement was determined. The thickness of the consolidated volcanics and/or sediments decreases from about 4.5 km. to .5 km. away from Bermuda, and the thickness of the unconsolidated sediment decreases from about .8 km. to about .1 km. away from Bermuda. The boundary between these two layers corresponds with the "M" reflection horizon of deep sea reflection measurements. Important structural features are the depressions in the basement and the disappearance of the Mohorovicic discontinuity on the Bermuda Rise. On the profiles made in the vicinity of the Bermuda Islands, the truncated cone of the Bermuda volcanoes is measured with an average velocity of 4.25 km/sec. The results of the depth calculations from these profiles, the deep boring on Hamilton Island, and the known geology of the islands are in agreement with Daly's (1910) hypothesis on the effects of glaciation in atolls.

CONTENTS

TEXT

	Page
Introduction	778
Equipment	778
Acknowledgments	778
Method of investigation	780
Interpretation of data	781
Travel-time data and geophysical results	783
General statement	783
A. Bermuda Rise profiles	783
B. Nares Basin profiles	785
C. Bermuda profiles	788
Identification of refraction layers	793
Interpretation of structure	800
Seismology	807
References cited	807

ILLUSTRATIONS

Figure	Page
1. Geologic location of Bermuda Refraction profiles	779
2. Ray diagram of refraction, reflection, and direct arrivals	781
3. Bottom and surface-bottom reflections	782
4. Atlantis 164—Caryn 17 profiles 30, 31, 36	784
5. Atlantic 164—Caryn 17 profiles 32, 33	786
6. Atlantis 164—Caryn 17 profile 34	787
7. Atlantis 164—Caryn 17 profile 35	788
8. Atlantis 164—Caryn 17 profiles 4, 5	789
9. Atlantis 164—Caryn 17 profile 19	790
10. Atlantis 172—Caryn 22 profile 20	792
11. Atlantis 172—Caryn 22 profile 21	793
12. Atlantis 172—Caryn 22 profile 22	794
13. Atlantis 172—Caryn 22 profile 23	795
14. Atlantis 172—Caryn 22 profile 24	796
15. Atlantis 172—Caryn 22 profiles 25, 26	797
16. Section of Pirsson boring	799
17. Geologic section A	801
18. Geologic section B	802
19. Isopach map of unconsolidated sediment and consolidated volcanics and sediments	803
20. Contour map of bottom and basement	804
21. Geologic section C	805
22. Seismic sections	806

Plate	Facing Page
1. Location of refraction profiles in the North Atlantic	777
2. Geographic location of refraction and reflection stations	778
3. Sample refraction records	782
4. Sample reflection records	783

Introduction

During the summer of 1950 an extensive two-ship refraction operation was made on ATLANTIS #164 and CARYN #17 cruises. A total of 70 refraction stations were made on tracks from Bermuda to Charleston, South Carolina; Norfolk, Virginia, to Bermuda; Bermuda to the Nares Deep[1]; Bermuda to Halifax, Nova Scotia; Halifax to Sable Island; and Halifax to Woods Hole, Massachusetts. During the spring of 1951, the opportunity arose to make an additional series of deep-sea refraction stations on ATLANTIS #172 and CARYN #22 cruises. Thirty-three profiles were made covering the Caribbean, the Puerto Rico trough, and tracks from Puerto Rico to Bermuda, and Bermuda to Woods Hole. Plate 1 shows the geographic location of the refraction stations.

The results and interpretations of profiles taken in Bermuda, over the southern and southeastern part of the Bermuda Rise, and over the northern part of the Nares Basin are discussed in this paper. These include ATLANTIS #164–CARYN #17 profiles 4, 5, 30, 31, 32, 33, 34, 35, and 36, and ATLANTIS #172–CARYN #22 profiles 19, 20, 21, 22, 23, 24, 25, and 26. The shooting tracks and receiving positions of the two ships are shown in Plate 2 and Figure 1.

The platform on which the Bermuda Islands, Challenger Bank, and Plantagnet (Argus) Bank are located is a series of volcanic peaks (Pirsson, 1913; Piersson and Vaughn, 1914) covered by alternating sections of marine limestones, eolianites, and fossil soils of Quaternary age (Sayles, 1931). A steep slope, which averages about 6° along our line of profiles but exceeds 8° in parts, forms the side of the platform. The depth increases from .2 km (100 fathoms) to 4.2 km (2300 fathoms) in 37 km (20 nautical miles). The gentler slope of the Bermuda Rise prevails for approximately the next 500 km (270 nautical miles) on the south and east, carrying the depth from 4.2 to 5.3 km (2300 to 2900 fathoms), with a slope of about 2.6 m per km (16 ft. per nautical mile). On the west the Bermuda Rise extends to about 300 km (19 nautical miles) from Bermuda (Tolstoy, 1951).

[1] The term Nares Basin is used here to denote the deep basin (>5.3 km (2900 fathoms)) south of the Bermuda Rise, extending to the ridge just north of the Puerto Rico trough (Tolstoy, 1951).

Equipment

Both the ATLANTIS and the CARYN used two hydrophones and two separate amplifying systems in their recording operations. This was done to insure against spurious arrivals, only those signals received on both hydrophones being taken as genuine refractions. All the hydrophones were Brush Development Company, Type AX58, consisting of two Rochelle salt crystals connected in series and immersed in castor oil for proper matching to the water and mounted with a cathode follower preamplifier to match the crystal to the hydrophone cable.

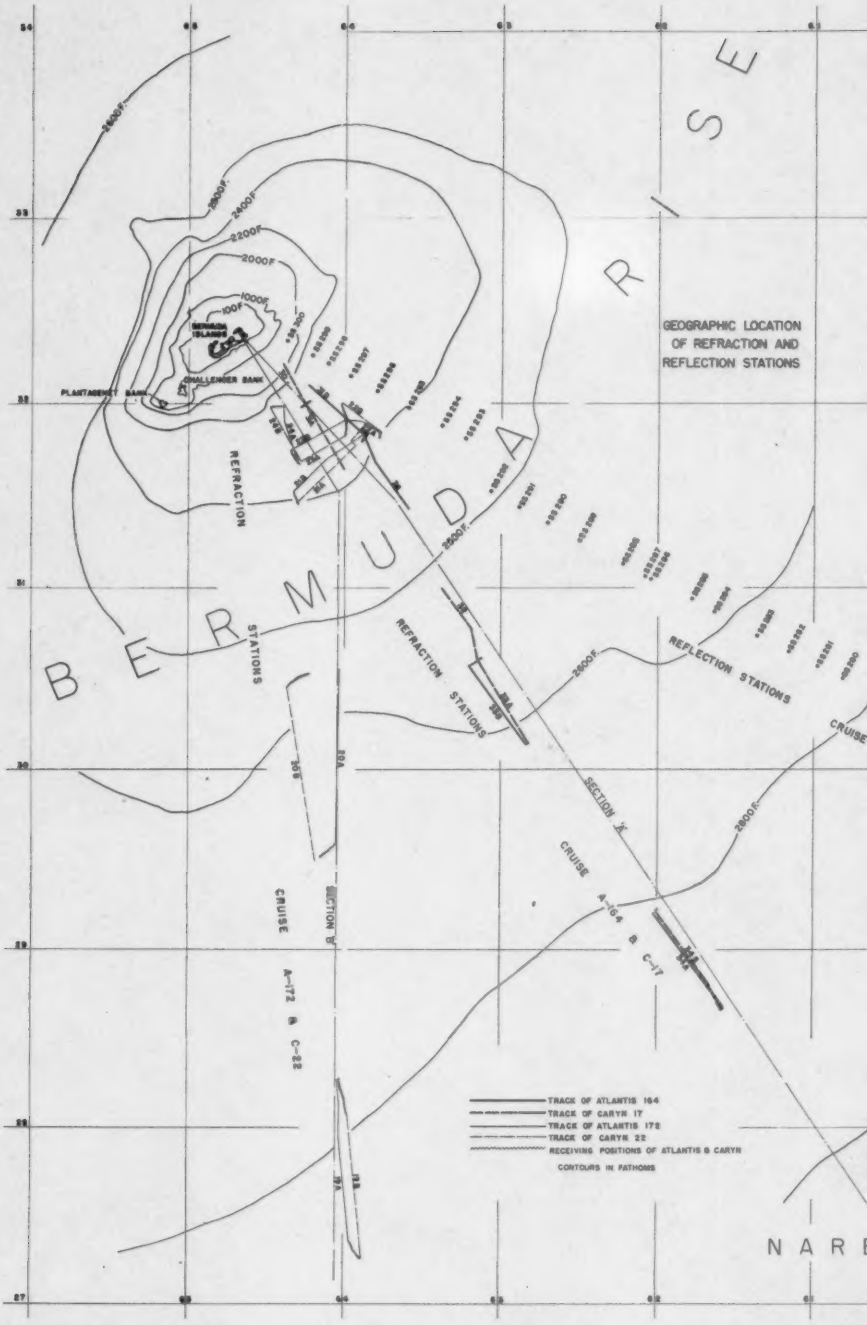
The main amplifying system on ATLANTIS #164 was a five-channel underwater sound analyzer, designed by W. Dow, with five separate interstage filter channels. Only four of the channels were used.

Acknowledgments

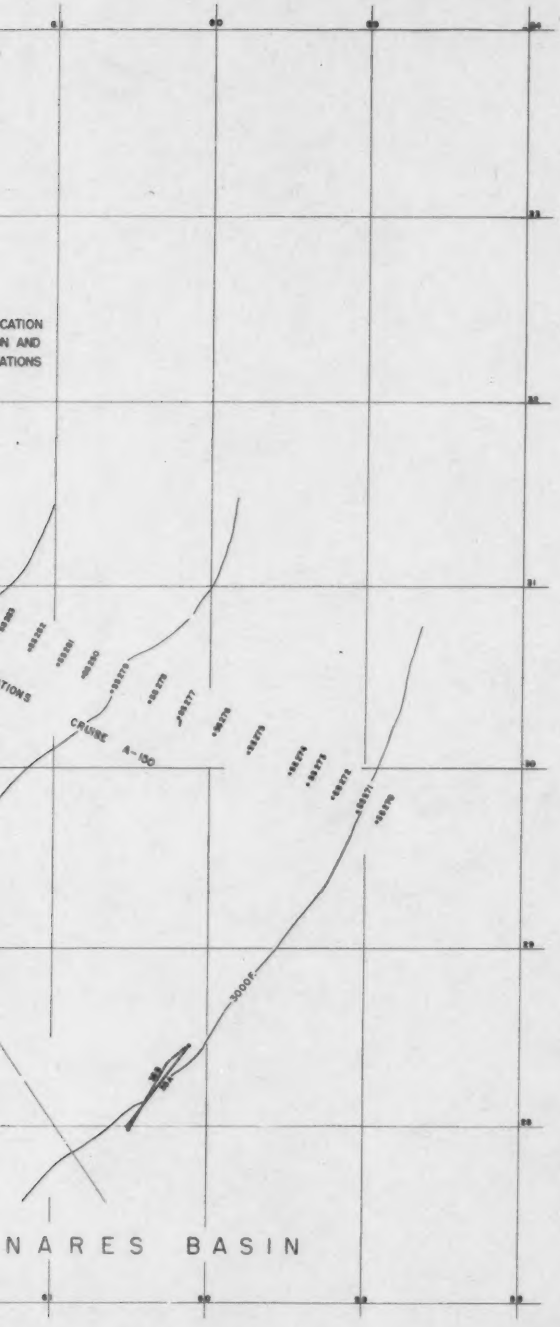
This research was carried out under Contract NObsr-43355 with the Bureau of Ships, U. S. Navy, and Contract N6-onr 271 Task Orders 13 and 24 with the Office of Naval Research. The Bureau of Ordnance of the U. S. Navy supplied the explosives that were used.

The Woods Hole Oceanographic Institution served as the operating base and made available the research vessels ATLANTIS and CARYN. The cooperation of Captain A. K. Lane and the crew of the ATLANTIS, and Captain J. Pike and the crew of the CARYN were important to the success of the operation.

To those members of the scientific party of the ATLANTIS and CARYN who took part in the refraction investigation with the authors and without whose help the investigation would not have been possible, acknowledgment is gratefully given: to G. H. Sutton, B. C. Heezen, R. S. Edwards, and E. G. Smith, Lamont Geological Observatory; T. Madden, Teaching fellow in geology, Massachusetts Institute of Technology; J. Northrop, instructor, Bates College; Dr. H. J. Pincus, Assistant Professor



GEOGRAPHIC LOCATION OF REFRACTION AND REFLECTI



REFLECTION STATIONS

Ohio State University; G. Duys and L. Davis, Woods Hole Oceanographic Institution; R. C. Dubois, C. R. Bentley, and M. G. Cheney, Jr., graduate student in geophysics, Columbia University; and G. Shaeffer and J. Hazelworth, Hydrographic Office, U. S. Navy.

The assistance and cooperation of Rear Admiral (ret, U. S. C. G.) E. H. Smith, director, Drs. C. O'D. Iselin, J. B. Hersey and G. Oakley, Woods Hole Oceanographic Institution; and Dr. J. L. Worzel, assistant director, Lamont Geological Observatory, were of great help in planning and supporting the operation.

The authors thank G. Hamilton and the personnel of the Navy SOFAR Station, St. David's Island, Bermuda, for their assistance and for the use of the buoy boat.

The first channel (Pl. 3) had a 5000-cycle high-pass filter, recording both a high- and low-gain setting through a rectifier. This channel was used for the clear reception of the direct water wave, travelling through the surface sound channel, and the bottom-reflected waves. The remaining channels were unrectified and were used for the identification of the refraction arrivals. The second channel was an all-pass channel; the third a 100-cycle low pass; and the fourth a 20-cycle high pass, recording both the high- and low-gain settings. The 20-cycle high-pass channel was of particular advantage in the

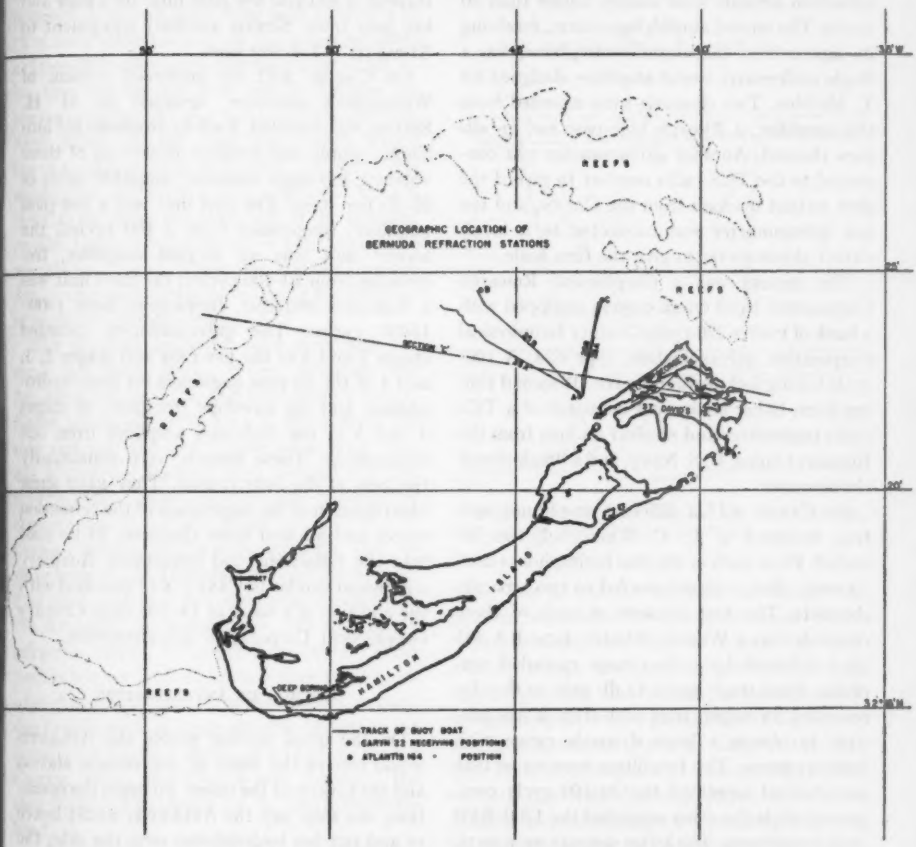


FIGURE 1.—GEOGRAPHIC LOCATION OF BERMUDA REFRACTION PROFILES

deep-water refraction measurements since most of the extraneous noise due to the rolling of the ship, the slapping of the waves, and the bending of the cable was 20 cycles or lower, whereas the refraction arrivals were usually higher than 20 cycles. The second amplifying system, receiving its signals from the second hydrophone, was a single underwater sound amplifier, designed by T. Madden. Two channels were recorded from this amplifier, a 20-cycle high-pass and an all-pass channel. Another galvanometer was connected to the TCS radio receiver to record the shot instant markers from the CARYN, and the last galvanometer was connected to a break circuit chronometer to give the time scale.

The camera was a Geophysical Research Corporation hand crank camera equipped with a bank of twelve 220-cycle Century Geophysical Corporation galvanometers, type 614. A 100-cycle tuning fork oscillator gave .01 second timing lines. Other equipment consisted of a TCS radio transmitter and receiver on loan from the Bureau of Ships, U. S. Navy, and a break circuit chronometer.

On CARYN #17 a different amplifying system, designed by P. C. Wuenschel, was installed. From each of the two hydrophones used on every shot, a signal was fed to two separate channels. The first element of each of these channels was a Western Electric type RA 363 filter followed by a four-stage cascaded amplifier. Each stage had a 12 db gain so that by recording an output from each stage it was possible to obtain a large dynamic range with linear response. The two filters were set so that one channel amplified the 20–100 cycle component while the other amplified the 1200–8000 cycle component. The latter outputs were rectified to record the envelope of the high-frequency arrivals. Only the low-frequency channels were recorded from the second hydrophone. Two of the galvanometers were used to record the chronometer and the time breaks from the shooting ship.

A Texaco Company camera was used. Auxiliary equipment consisted of a Brush recorder and amplifier, a TCS radio transmitter and receiver, an RBS radio receiver, and a break circuit chronometer.

The five channel amplifier was used again on ATLANTIS #172 cruise. Two gains on the high-frequency rectified channel and two gains of a 30-cycle low-pass channel were recorded. A second under-water sound amplifier was used to record signals from the second hydrophone through a 30-cycle low-pass filter on a high and low gain trace. Similar auxiliary equipment to ATLANTIS #164 was used.

On CARYN #22 an improved version of Wuenschel's amplifier, designed by G. H. Sutton, was installed. Each hydrophone led into similar amplifying systems, consisting of three separate five-stage cascaded amplifier units of 20 db per stage. The first unit was a low-pass amplifier, frequencies from 2–100 cycles; the second unit was an all-pass amplifier, frequencies from 20–500 cycles; the third unit was a high-pass amplifier, frequencies from 1000–15000 cycles. The galvanometers recorded stages 2 and 3 of the low-pass and stages 2, 3, and 4 of the all-pass amplifiers for both hydrophones, and the envelope (rectified) of stages 4 and 5 of the high-pass amplifier from one hydrophone. These records were consistently the best of the four cruises. They gave surer identification of the beginnings of the refraction waves and allowed more character to be read into the reflections and refractions. Auxiliary equipment similar to CARYN #17 was used with the addition of a bank of 14–220 cycle Century Geophysical Corporation galvanometers.

METHOD OF INVESTIGATION

On the usual reverse profile the ATLANTIS would receive the shots at one reverse station and the CARYN at the other. To begin the operation, one ship, say the ATLANTIS, would heave to and put her hydrophones over the side; the CARYN would then proceed away from her, firing from 6 to 20 shots to make up half of a reversed profile. The size of the charges would vary from 1 to 10 pounds of TNT-tetryl for the close shots and from 50 to 300 pounds for the more distant shots. The length of the profiles would run from 20 to 60 miles depending on the receiving conditions, the amount of explosives available, and the amount of information desired. Most of the shots were fired by safety fuse, although some of the smaller charges were fired electrically on demolition cable. Ample warning was given to the receiving ship prior

to the detonation of the shot to allow them to slack their hydrophones so that they would be sinking slowly at the incidence of the refraction arrivals. This was exceedingly important in order to keep the background noise as low as possible. The close shots were fired at from 5 to 15 minute intervals and the more distant shots at from 30 to 60 minute intervals, always allowing time for the receiving ship to develop the previous record and plot the refraction arrivals. After firing the last shot, the CARYN would heave to and prepare to receive. The ATLANTIS would then get underway and proceed toward the CARYN, firing the other half of the reversed profile. Upon coming abeam of the CARYN, the operations would either be secured or the ATLANTIS would proceed past firing the first half of another reversed profile.

The shooting procedure was essentially the same on both ships. When shooting, the ATLANTIS received the shot instant on a hydrophone permanently located in the hull of the ship and sent the shot instant along with various identifying markers over the radio to the CARYN. The CARYN recorded this information through one of the galvanometers onto the refraction record. At the same time the shot instant from the hull hydrophone and the markers that were sent over the radio were recorded on the ATLANTIS for comparison with the CARYN refraction record. Frequent chronometer checks were made on both ships to insure the knowledge of absolute time of the shot instant in case, due to poor radio contact, the shot instant or the identifying markers were not picked up by the CARYN. When the CARYN was shooting, the shot instant was picked up on the fathometer head.

Bathythermograph observations were taken along the profile in order to determine the velocity of sound in the surface water layers. A continuous recording fathometer tape was also taken along the shooting tracks.

INTERPRETATION OF DATA[2]

On the typical record, three types of arrivals were received—the refraction waves from basement and the sediments (G), the direct wave travelling through the surface sound channel (D), and the bottom-reflected waves (R) (Fig. 2). On most of the records, the refraction arrivals came in with a frequency of 40

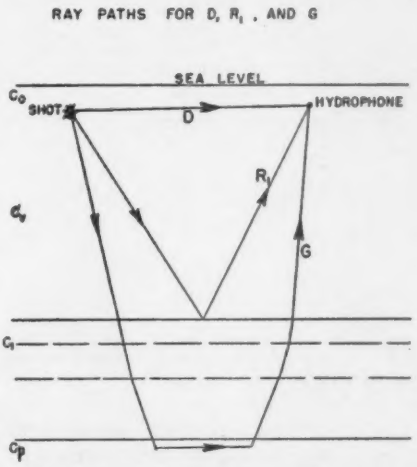


FIGURE 2.—RAY DIAGRAM OF REFRACTION, REFLECTION, AND DIRECT ARRIVALS

cycles per second. In addition to this arrival and commensurate with it, a 12 cycle per second arrival was obtained on some records. On other records, usually those which were received at long ranges, only the 12 cycle per second arrival was present. It was a peculiarity of all refraction measurements made in deep water that only these two frequencies were present in the refraction arrivals. No explanation of the phenomena is forthcoming at this time, but it is suggested that the single frequency characteristic is due to coupling between the sediments and the basement.

The direct water wave had a high frequency character and, except at short distances, was received only on the high-frequency rectified traces. Depending on the depth of the surface sound channel, the direct wave was received out to ranges from 6 to 30 miles. Further, the reception of this wave was critically dependent on the depth of the shot, i.e., whether the shot was fired in the surface sound channel or in the underlying thermocline.

[2] This section is discussed in more detail by Officer and Wuenschel (1951).

The bottom reflected waves were recorded on all frequency channels and were the most prominent feature on the records. Besides the first reflected wave, the second, third, and later reflections were received. Sharp arrivals for the second and later reflections could be picked

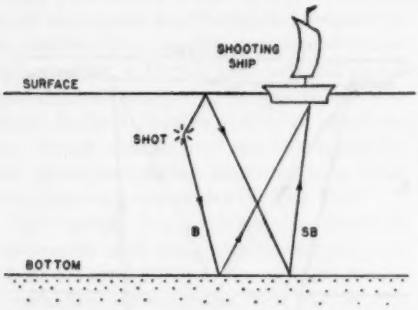


FIGURE 3.—BOTTOM AND SURFACE-BOTTOM REFLECTIONS

only on the high-frequency channel. These reflections were strong on the low-frequency channels but their beginnings were gradual. For the first reflection, high- and low-frequency channels gave strong, coincident readings.

Numerous corrections and calculations had to be made before the final travel-time curves could be drawn. A correction had to be made for the time taken for the sound to travel from the shot to the shooting ship. For this calculation it was necessary to know the speed of the shooting ship, the time interval elapsed from the instant the charge was thrown over the side to the instant of detonation, and the depth of the shot. The depth of the shot was determined from the time difference between the bottom reflection and the surface-bottom reflection, as recorded on the shooting record (Fig. 3). Since the sea surface was chosen as the surface of reference, a second correction had to be made for the depth of the shot and the hydrophone (Officer and Wuenschel, 1951). A third correction had to be made for irregularities in the bottom topography. Since the thickness of the basement cover was of the order of a mile, it was reasonable to consider that the bottom topography did not represent the topography in the basement but rather the topography in the lithified material above it. Two other possibilities were tried: variations in the thickness of the unconsolidated sediments or variations in the basement topography; but it was found that correcting for the topography as irregularities in the lithified material above the basement was the most effective in freeing the points of the G curve from the irregularities in bottom topography. Those corrections were usually very small.

In order to insure confidence in the data and to bring out any irregularities, plots of R^2 vs. D^2, similar to those discussed by Ewing, Worzel, Hersey, *et al.* (1950), were made. The high frequency arrivals were plotted as straight lines, determined by the equation

$$R_n^2 = \frac{c_0^2}{c_1^2} D^2 + (2n)^2 \frac{h_1^2}{c_1^2} \qquad (1)$$

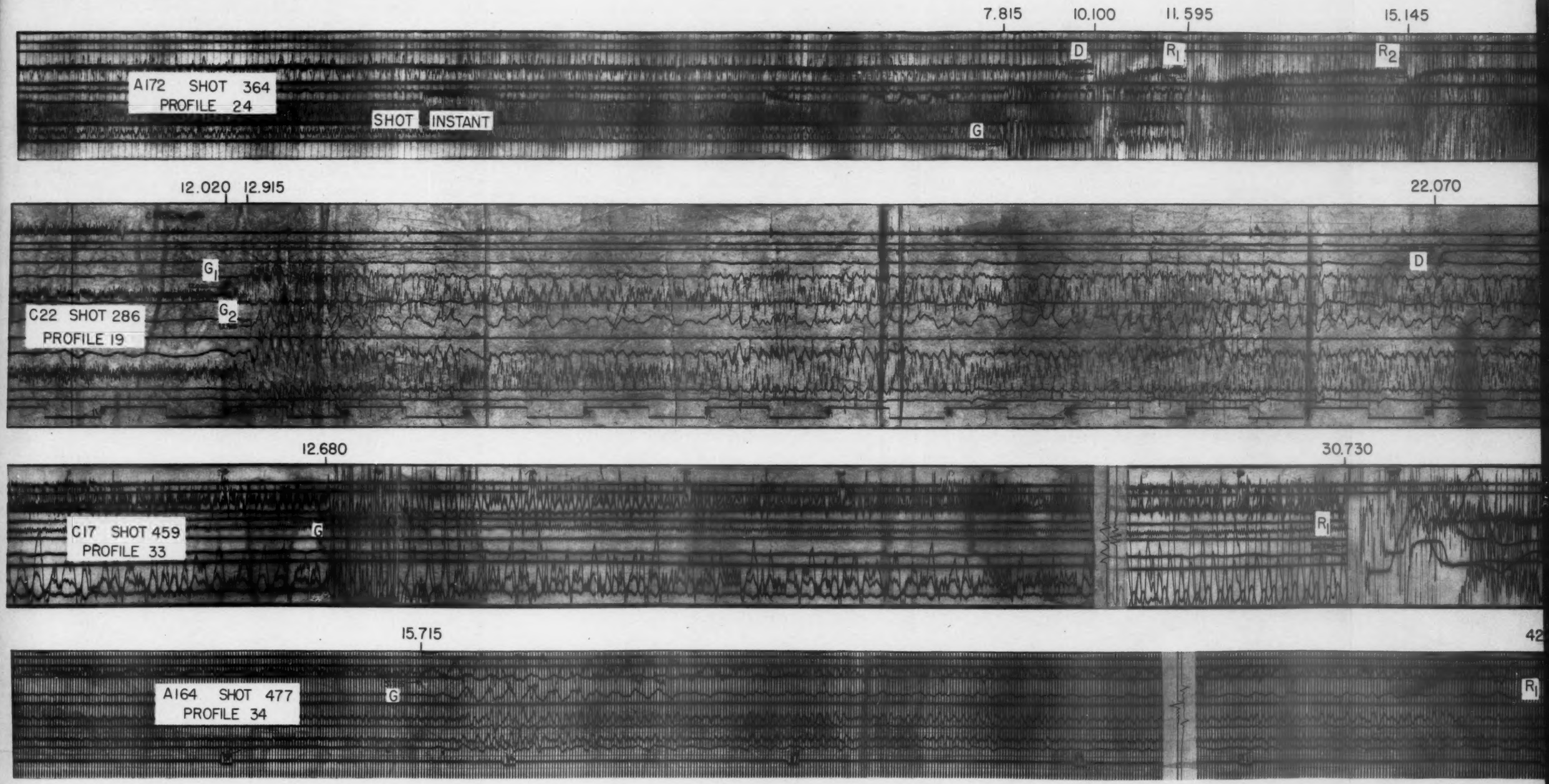
where D = travel time of direct wave
R_n = travel time of nth reflection
h_1 = depth of water
c_0 = surface sound velocity
c_1 = average vertical sound velocity.[3]

From the slope of the line and c_0, a value for the average vertical sound velocity was obtained. The value determined for the profiles agreed within the accuracy of the plot with the values quoted in the British Admiralty Tables (1939); and for the sake of standardization and comparison with other refraction results the values given in the Tables were used in the subsequent calculations. On those shots for which no D was obtained, it was necessary to use the reflection arrivals and the R^2–D^2 plots to calculate the range. For some of the longer shots, 55 km. (30 naut. mi.) or greater, curved ray path calculations were made to determine D. It is estimated that no serious error was introduced into the determination of the travel-time curves rfom this source.

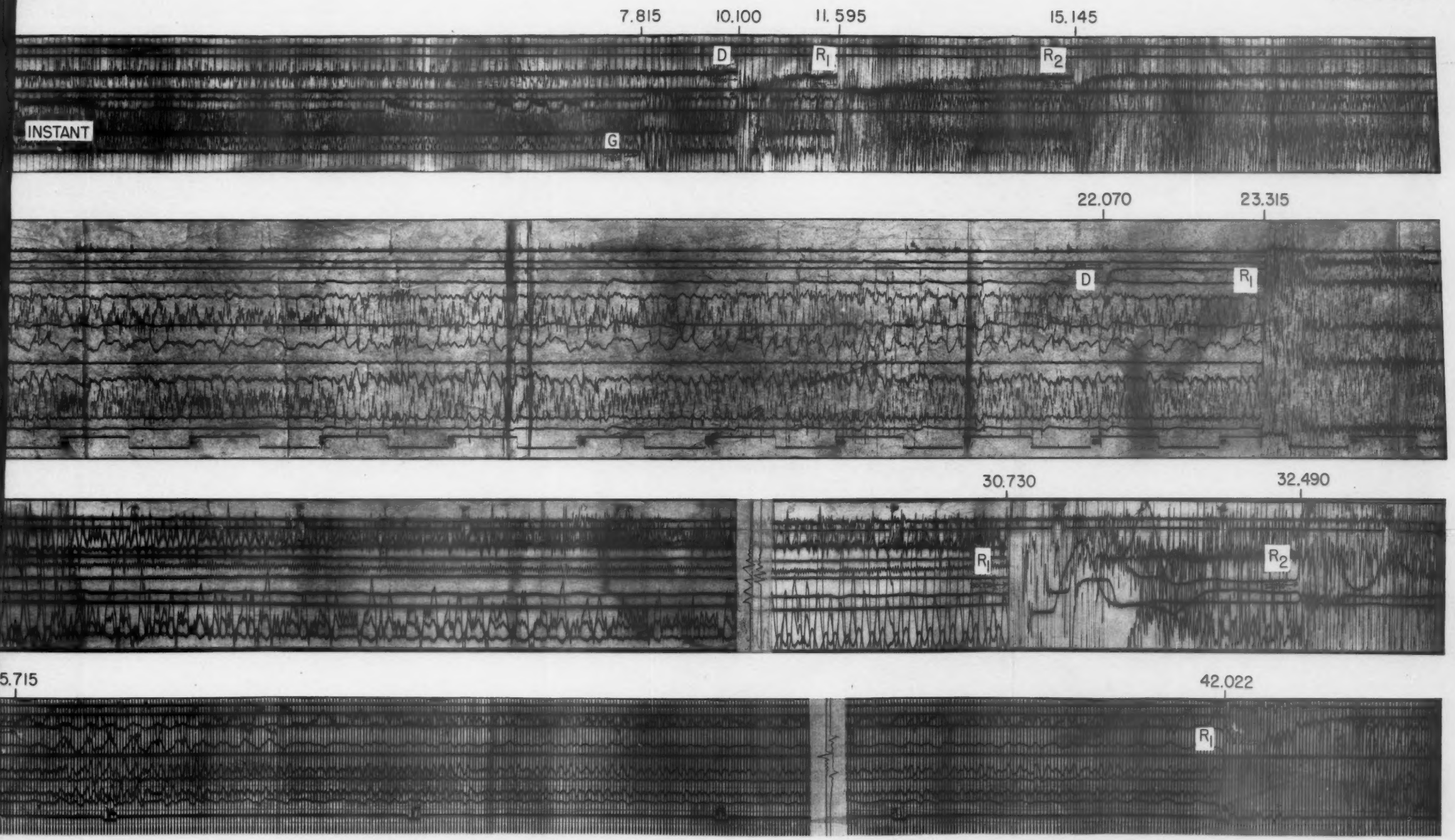
As a further check on the validity of the data, plots of the time of detonation versus D

[3] Average vertical sound velocity is defined as the "time average" of the sound velocity in water taken from the sea level to the bottom. It is that velocity which when multiplied by the echo time will give the true depth.

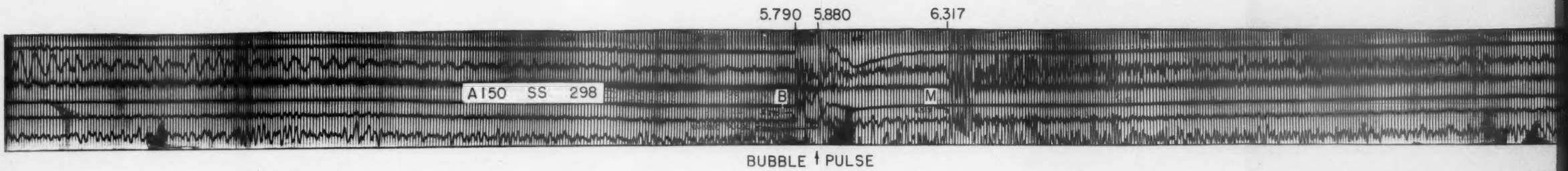
$$\overline{V} = \frac{H}{\int_0^H \frac{dh}{V}} \quad \text{not} \quad \frac{1}{H}\int_0^H V\,dh$$

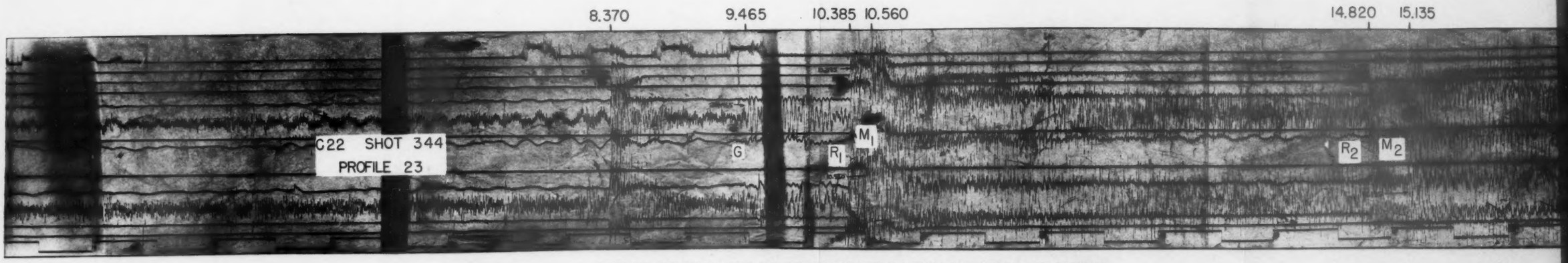


SAMPLE REFRACTION RECORDS FROM ATLANTIS 164 & 172 AND CARYN 17 & 22

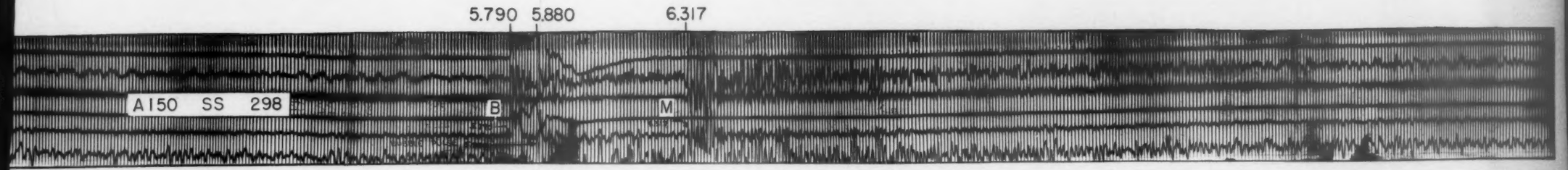


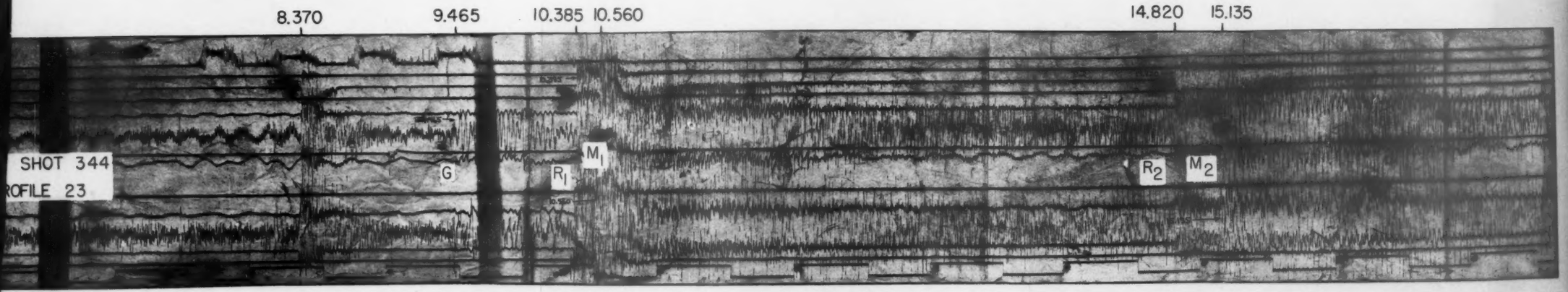
SAMPLE REFRACTION RECORDS FROM ATLANTIS 164 & 172 AND CARYN 17 & 22





VERTICAL AND WIDE-ANGLE "M" REFLECTION RECORDS FROM ATLANTIS 150 AND CARYN 22





VERTICAL AND WIDE-ANGLE "M" REFLECTION RECORDS FROM ATLANTIS 150 AND CARYN 22

ere made. These plotted essentially as straight nes, depending on the constancy of the shooting ship's speed.

An accurate value of the surface-sound velocity was determined from the bathythermograph data taken along the shooting track and the salinity values typical for the area and season (Fuglister, 1947). A value of 1.539 km. per sec. (5050 ft. per sec.) was obtained for the ATLANTIS #164–CARYN #17 profiles and a value of 1.522 km. per sec. (4992 ft. per sec.) for the ATLANTIS #172–CARYN #22 profiles.

TRAVEL-TIME DATA AND GEOPHYSICAL RESULTS

General Statement

The principles used in the interpretation of these results are those generally used in geophysical refraction work and will not be repeated here (Ewing, Worzel, Steenland, and Press, 1950). Some details, peculiar to deep sea refraction measurements, are worthy of mention here.

The travel-time data are plotted as functions D, i.e., range in units of surface sound velocity. The equation of the refraction line will then be given by an equation of the form,

$$G = \frac{c_0}{c_p} D + \sum_{n=1}^{p-1} 2 \frac{h_n \sqrt{c_p^2 - c_n^2}}{c_n c_p} \qquad (2)$$

where G = travel time of refracted wave
D = travel time of direct wave
c_0 = surface sound velocity
c_n = average vertical velocity of each layer
c_p = velocity of the refracting layer
h_n = thickness of each layer

so that the velocity of the refracting layer is determined by the product of the inverse slope and the surface sound velocity.

Because of the velocity structure in the water (Ewing and Worzel, 1948), the formula for the intercept in equation (2) is approximate. However, calculations from ray theory in a variable velocity medium show that the approximate formula is valid to .002 seconds for refracting velocities greater than 6.1 km. per sec. (20000 ft. per sec.) and is valid to .01 seconds for velocities greater than 1.7 km. per sec. (3600 ft. per sec.) so that the approximate formula can be used with negligible error for the depth calculations.

For each profile, the best straight line was drawn graphically satisfying the conditions imposed by the results of each shot, the reverse points on reverse profiles, and the intercepts on end-to-end profiles. The values for the depths and velocities of the refracting layers are determined from equation (2). All travel-time curves are presented in the present paper with shot distances reduced to kilometers as well as direct water-wave travel time.

A. Bermuda Rise Profiles

This set includes ATLANTIS #164–CARYN #17 profiles 30, 31, 36, 32, and 33 and ATLANTIS #172–CARYN #22 profiles 20, 21, 22, 23, and 24. Three refracting layers were determined—a low velocity layer coincident with the bottom of the ocean, an intermediary velocity layer a few hundred to a few thousand feet beneath, and a high-velocity basement several thousand feet beneath. Profiles 21 and 23 were shots parallel to the contours of the bottom topography; all the other profiles were shots perpendicular to the contours.

Profiles 30, 31, and 36 form a reverse pair and two end-to-end profiles. The high-velocity basement is well determined on all profiles (Fig. 4). There are no serious discrepancies of any of the points from the calculated refraction line, and the depths and velocities of the basement are well determined. The intercepts of the end-to-end profiles agree well. Since the two parts of the reverse profile were shot on different days, the reverse distance had to be determined from the combined navigation of the ATLANTIS and CARYN. This does not give an accurate determination, and the reverse points agree within the expected error.

The intermediary velocity layer was measured by one point on profile 31B and one point on 36, a true velocity being computed from the two measurements. With the given shot distribution and the thickness of this layer, it was not possible to measure it under 31A and 30. The low-velocity layer, coincident with the bottom of the ocean, as indicated by tangency to the

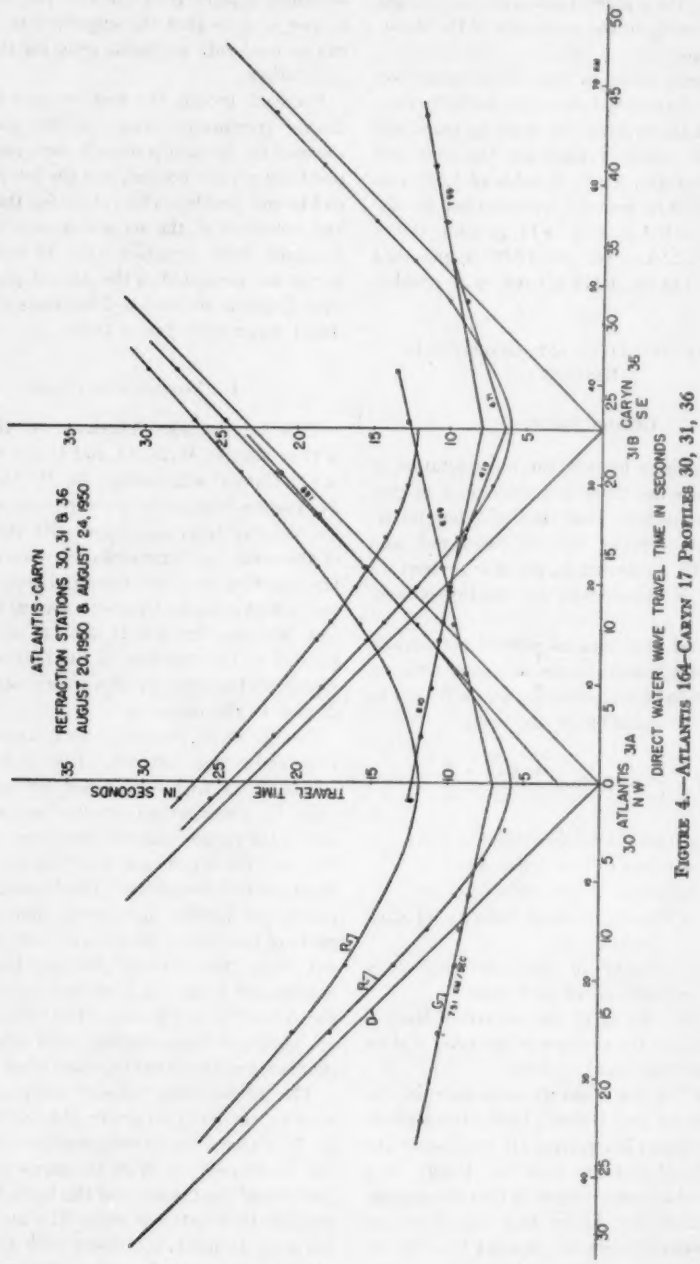


FIGURE 4.—ATLANTIS 164–CARYN 17 PROFILES 30, 31, 36

reflection curve, was determined by three points on profile 31A.

The great depth to basement at 31B–36 arises from the apparent velocities for basement, 8.10 km/sec (26570 ft/sec) and 7.95 km/sec (26100 ft/sec) found for these two profiles and from the value 6.49 km/sec (21290 ft/sec) obtained for 31A. In the interpretation it is considered that the true basement velocity found from 31A and 31B applies to profiles 30 and 36. The velocities of the overlying layers affect the actual depths obtained but not the general basement configuration.

Profiles 32 and 33 form a reverse pair and an end-to-end profile. The basement line is well determined on both profiles (Fig. 5). The last point on 32 is abnormally high and the first point on 33A abnormally low. The intercepts of the end-to-end profile and reverse points of the reverse profile agree well. The intermediary velocity layer was measured on 32, but with the given shot distribution it was not possible to see it on either 33A or 33B. The basement velocity found from 33A and 33B was used in computing the basement slope on 32.

Profile 20 was the longest one made. Refraction arrivals were received out to a distance of 100 km. (56 naut. mi.). On both 20A and 20B, the arrivals plotted on a single high-velocity line. There was no break in this line to indicate a higher velocity medium below the basement separated from it by a discontinuity. There does seem to be a gradual increase in velocity from the close shots to the more distant shots, but this cannot be measured quantitatively with the data at hand. There is a good determination of the basement on both halves of the profile, and it reverses well (Fig. 10). The intermediary velocity layer was measured on 20B. Because of an error in ship's navigation, it was not possible to obtain the near points on 20A.

On profile 21 it was necessary to insert a fictitious station (Ewing, Worzel, Steenland, and Press, 1950), in order to interpret the refraction data (Fig. 11). A good determination of velocity and depth is obtained from both parts of the profile, and it shows that the basement steeply from both ends of the profile toward the fictitious station. The intermediary velocity layer was not measured on this profile.

Profile 22 was very short, but it gives a reasonably good determination of the basement (Fig. 12). There is a good reverse, and the intermediary velocity layer was measured on 22A.

On profile 23 it was necessary to introduce a fictitious station (Fig. 13). The left-hand part of this profile gives a good determination of the basement, but on the right-hand part a good determination was obtained only on one-half of the profile. The single point on the other half of this part gives an apparent velocity of 4.49 km/sec (14730 ft/sec) and could be measuring either the intermediary layer or the reverse of the high velocity basement. For the depth calculations the true velocity determined for the first part of 23 was applied to the second part in order to determine the slope and depth of the basement there. The basement was found to dip toward the fictitious station from both ends of the profile, similar to the results of 21. This was the only other profile to determine the low-velocity layer. Again the low-velocity refraction line was tangent to the reflection curve.

Profile 24 gives a good measurement of the intermediary velocity layer and the high-velocity basement. All lines are well determined and the reverses are good (Fig. 14).

B. Nares Basin Profiles

This set includes ATLANTIS #164–CARYN #17 profiles 34 and 35 and ATLANTIS #172–CARYN #22 profile 19. Four refracting layers were present under this group of profiles. Besides the three discussed in the previous section, a fourth layer is found beneath the basement. This layer is shown by a break in the high-velocity line to a still higher velocity. The break occurs at about 30 km. (16 naut. mi.) and corresponds to the Mohorovicic discontinuity.

Profile 34 gives a good determination of both high velocity media (Fig. 6). The reverses are good and there is little scatter of the points about the lines. The intermediary velocity layer was too thin to be measured, but for the depth calculations a thickness of .15 km. (500 ft.) extrapolated from near-by profiles was taken.

Profile 35 gives a good determination of the first high-velocity layer but a poor one of the second (Fig. 7). The beginnings of the ground

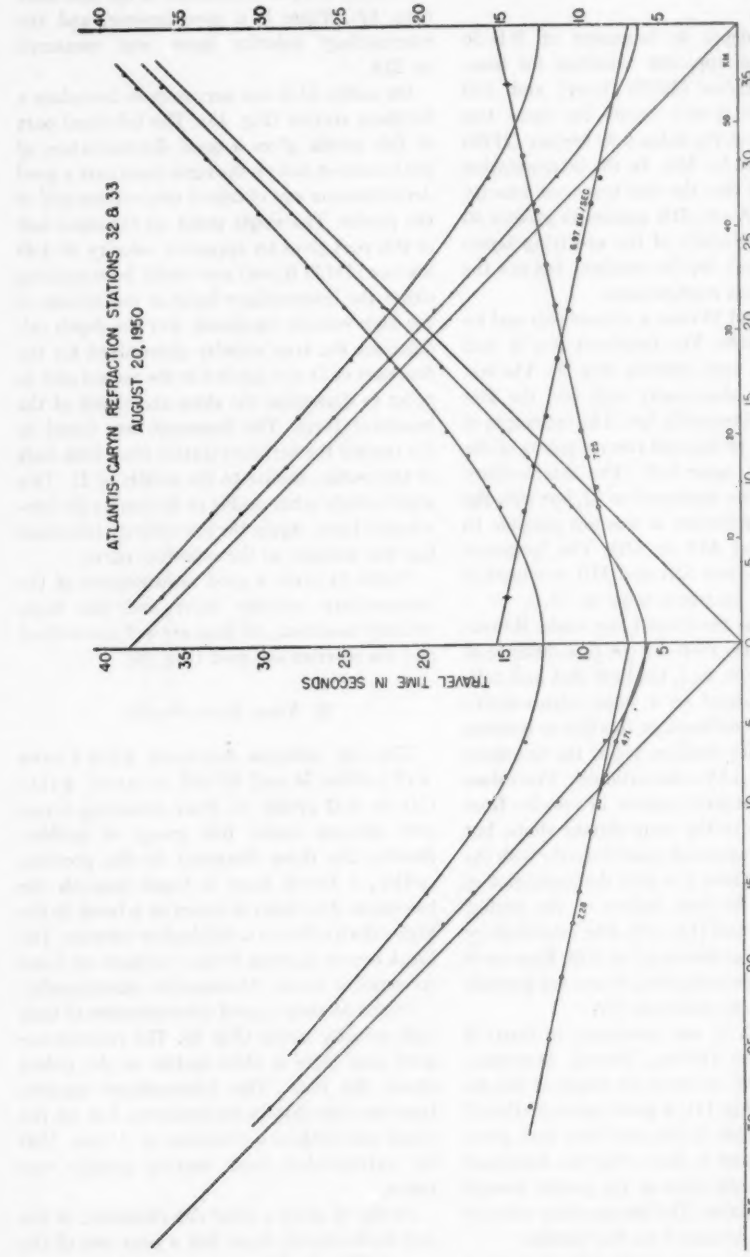

ATLANTIS-CARYN REFRACTION STATIONS 32 & 33
AUGUST 20, 1950
TRAVEL TIME IN SECONDS
ATLANTIS 32 NW 33A DIRECT WATER WAVE TRAVEL TIME IN SECONDS CARYN 33B SE
6.97 KM/SEC
7.15
7.71
7.28

FIGURE 5.—ATLANTIS 164-CARYN 17 PROFILES 32, 33

waves could not be read with assurance on the distant records, and the small lines associated with these points give an estimate of the time interval in which the refraction began. The intermediary velocity layer was picked up on 35B.

Profile 19 gives an excellent determination of both high-velocity layers (Fig. 9). The half received by CARYN #22 is particularly nice in that the first high-velocity layer can be picked up as a second arrival on the distant shots. The intermediary velocity layer was not thick enough to be measured, but in the calculations a thickness of .09 km. (300 ft.) was assumed. The second high-velocity basement has a considerably lower velocity, 7.49 km/sec. (24590 ft/sec.), than the values of 8.50 km/sec. (27900 ft/sec.) and 8.08 km/sec. (26520 ft/sec) found for profiles 34 and 35 respectively. However, since all three profiles show the same break in the velocity line and since they were all made in

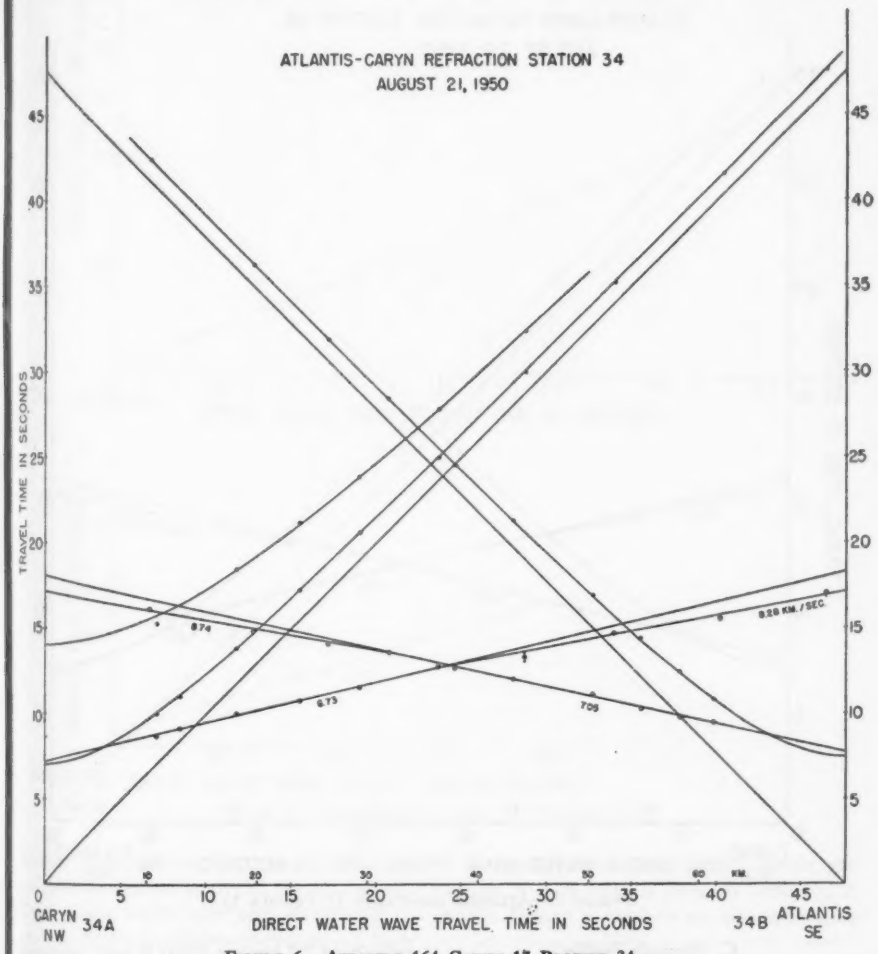


FIGURE 6.—ATLANTIS 164–CARYN 17 PROFILE 34

the same general area, the break on profile 19 is interpreted as indicating the Mohorovicic discontinuity also.

the shots do not carry in far enough to measure the eolianite and marine limestone above the basement (Fig. 15). For the depth calculations a

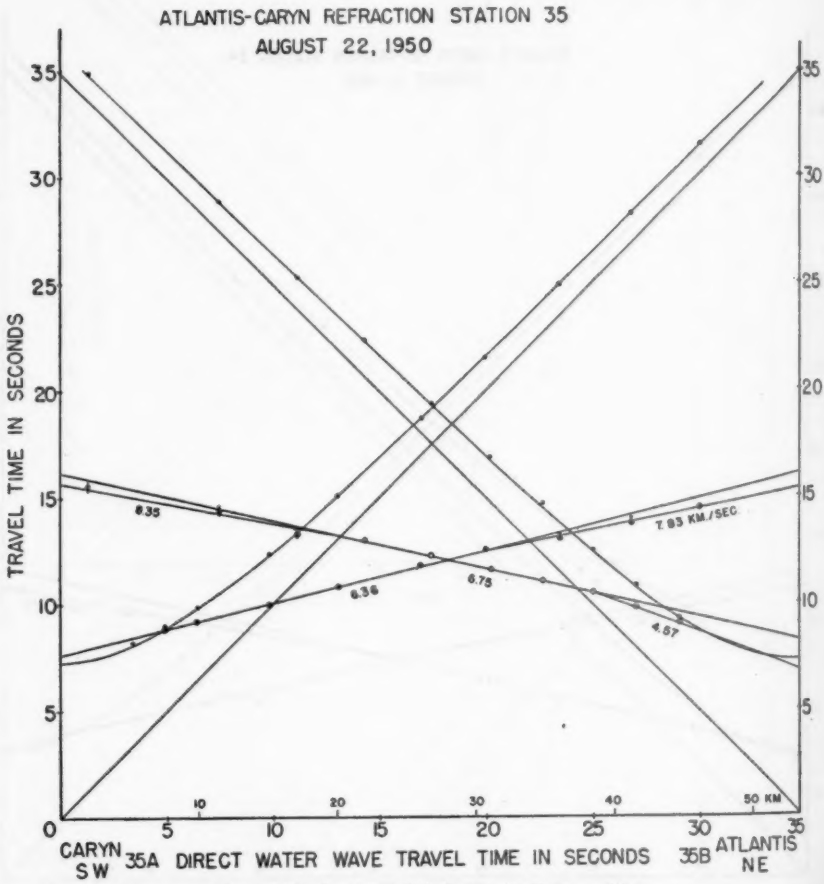


FIGURE 7.—ATLANTIS 164–CARYN 17 PROFILE 35

C. Bermuda Profiles

Four profiles were made in Bermuda during the summer of 1950 and spring of 1951 (Fig. 1). CARYN #22 received reversed profiles 25 and 26 in the lagoon and ATLANTIS #164 received unreversed profiles 4 and 5 in St. George's Harbor. The buoy boat from the Navy SOFAR station shot all the profiles.

Profiles 25 and 26 give a very good determination of the volcanic basement of Bermuda, but velocity of 2.7 km/sec (8800 ft/sec), measured by Woollard and Ewing (1939), is used. A little structure is seen at the end of 25A. This could be due to a horizontal change in basement velocity, an abrupt change in the depth of the volcanic basement, or a change in the overlying material. This one profile does not contain enough information to answer the question.

Profiles 4 and 5 are unreversed, profile 4 being shot east toward the ocean and profile 5 west toward the lagoon (Fig. 8). The true

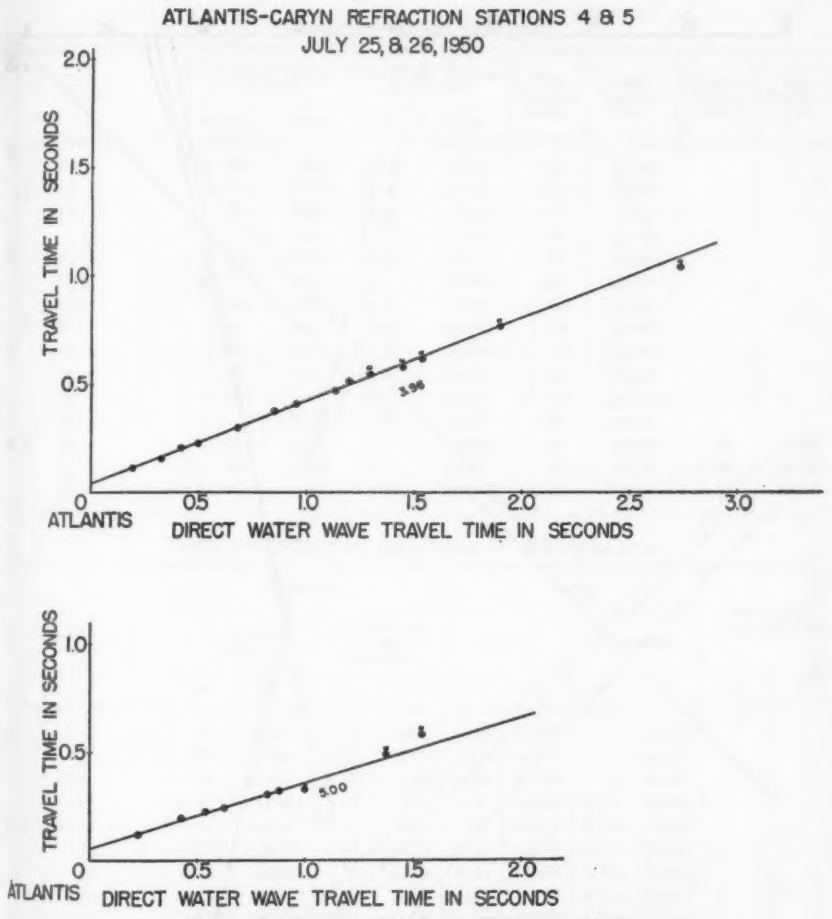


FIGURE 8.—ATLANTIS 164–CARYN 17 PROFILES 4, 5

velocity obtained from reversed profiles 24 and 25 is used in the depth and dip calculations. Those points which have been marked by an asterisk on the travel-time curves do not have an accurate range determination. They were shot behind the islands so that no water wave was received by the ATLANTIS. The range had to be determined from the buoy boat navigation, which was necessarily crude. Profile 5 shows the basement essentially flat, similar to the results of profiles 25 and 26. Profile 4, however, shows the basement dipping outward at an angle of 12°.[4]

A summary of the velocities, thicknesses, and depths of each layer is given in Tables 1, 2, and 3. Figures in brackets are assumed values

[4] M. Ewing, G. R. Hamilton, F. Press, and J. L. Worzel made two unreversed profiles in 1949 along almost the same tracts as profiles 4 and 5. Their unpublished results are similar to profiles 4 and 5. An apparent velocity of 5.43 km/sec (17800 ft/sec) is measured from the west profile and an apparent velocity of 4.21 km/sec (13800 ft/sec) for the east profile. The basement is at a depth of .09 km (300 ft.) under the receiving station. Considering the apparent velocity of the western profile as true, they obtain a slope of 10° for the basement on the eastern profile. In addition they measured the velocity of the eolianites and marine limestones as 2.7 km/sec (8800 ft/sec) in agreement with Woolard and Ewing (1939).

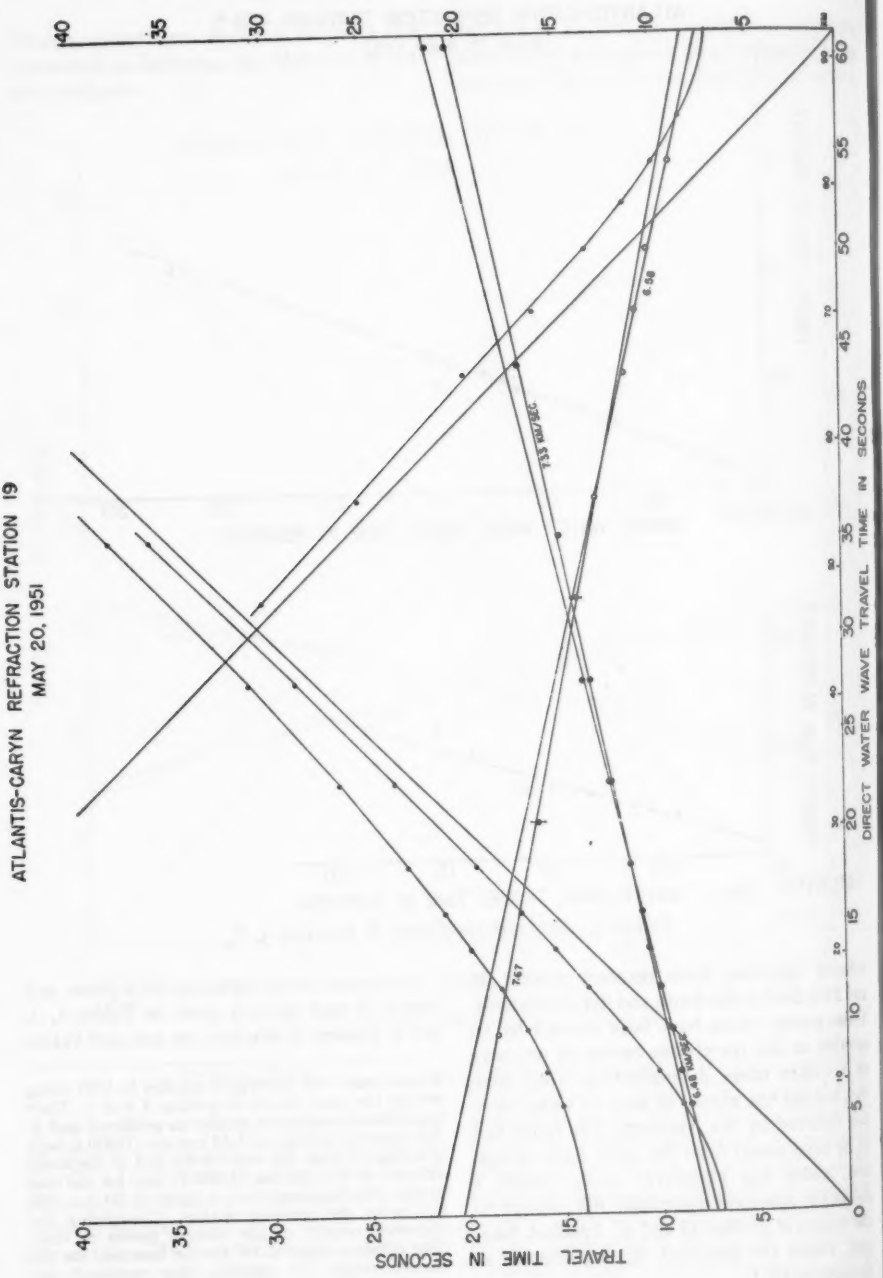
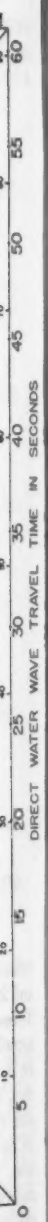

ATLANTIS-CARYN REFRACTION STATION 19
MAY 20, 1951
TRAVEL TIME IN SECONDS
DIRECT WATER WAVE TRAVEL TIME IN SECONDS
7.67
6.58

TABLE 1.—SEISMIC VELOCITIES

Profile	Unconsolidated Sediment		Consolidated Volcanics & Sediments		First Velocity, km/sec	High Basement, ft/sec	Second Velocity, km/sec	High Basement, ft/sec
	km/sec	ft/sec	km/sec	ft/sec				
24	(1.70)	(5590)	4.45	14590	7.73	25370		
22	(1.70)	(5590)	4.42	14500	6.86	22520		
23 (1)	1.70	5590	(4.49)	(14740)	6.67	21870		
(2)	1.70	5590	(4.49)	(14740)	(6.67)	(21870)		
21 (1)	(1.70)	(5590)	(4.41)	(14480)	6.90	22630		
(2)	(1.70)	(5590)	(4.41)	(14480)	7.55	24790		
36	(1.69)	(5560)	4.45	14590	(7.18)	(23550)		
31	1.69	5560	4.45	14590	7.18	23550		
30	(1.69)	(5560)	(4.45)	(14590)	(7.18)	(23550)		
33	(1.69)	(5560)	(4.71)	(15470)	7.10	23310		
32	(1.69)	(5560)	4.71	15470	(7.10)	(23310)		
20	(1.70)	(5590)	4.47	14670	7.52	24670		
34	(1.69)	(5560)	(4.51)	(14800)	6.81	22330	8.50	27900
35	(1.69)	(5560)	4.57	15000	6.54	21470	8.08	26520
19	(1.70)	(5590)	(4.51)	(14800)	6.53	21410	7.49	24590

TABLE 2.—THICKNESSES AND DEPTHS OF SEISMIC LAYERS

Profile	Thicknesses				Depths				Mohoronicic Discontinuity	
	Unconsolidated Sediment		Consolidated Volcanics & Sediments		Water		Basement			
	km	ft.	km	ft.	km	ft.	km	ft.	km	ft.
24 A	.44	1440	3.00	9860	4.30	14120	7.75	25410		
B	.85	2780	2.74	8990	4.30	14120	7.89	25890		
22 A	.52	1690	1.89	6220	4.59	15060	7.00	22970		
B	(.52)	(1690)	3.51	11520	4.59	15060	8.62	28270		
23 A_1	(.61)	(2000)	.79	2570	4.43	14540	5.83	19110		
B_1	(.73)	(2400)	4.74	15550	4.43	14540	9.90	32490		
A_2	(.73)	(2400)	4.83	15860	4.43	14540	9.99	32800		
B_2	.85	2800	1.00	3270	4.43	14540	6.28	20610		
21 A_1	.37	1210	0	0	4.43	14540	4.80	15750		
B_1	(.49)	(1600)	4.87	15980	4.43	14540	9.79	32120		
A_2	(.49)	(1600)	4.50	14780	4.43	14540	9.42	30920		
B_2	(.55)	(1800)	2.47	8090	4.43	14540	7.45	24430		
30	(.73)	(2400)	1.27	4180	4.41	14460	6.41	21040		
31 A	(.73)	(2400)	1.12	3660	4.50	14780	6.35	20840		
B	.76	2500	3.51	11510	4.50	14780	8.77	28790		
36	.70	2290	2.85	9350	4.66	15300	8.21	26940		
33 A	(.15)	(490)	2.60	8540	4.72	15480	7.47	24510		
B	(.15)	(490)	1.91	6270	4.72	15480	6.78	22230		
32	.15	490	2.48	8130	4.73	15530	7.36	24140		
20 A	.40	1310	1.00	3280	4.85	15920	6.25	20500		
B	(.40)	(1310)	2.95	9660	4.85	15920	8.20	26890		
34 A	(.15)	(500)	.33	1080	5.34	17520	5.82	19100	11.34	37210
B	(.15)	(500)	1.99	6510	5.34	17520	7.48	24530	10.81	35480
35 A	(.03)	(110)	.79	2580	5.71	18730	6.53	21420	10.22	33530
B	.03	110	2.64	8660	5.71	18730	8.38	27500	9.95	32630
19 A	(.09)	(300)	1.17	3850	5.30	17390	6.57	21540	8.07	26470
B	(.09)	(300)	1.92	6310	5.30	17390	7.31	24000	9.23	30280



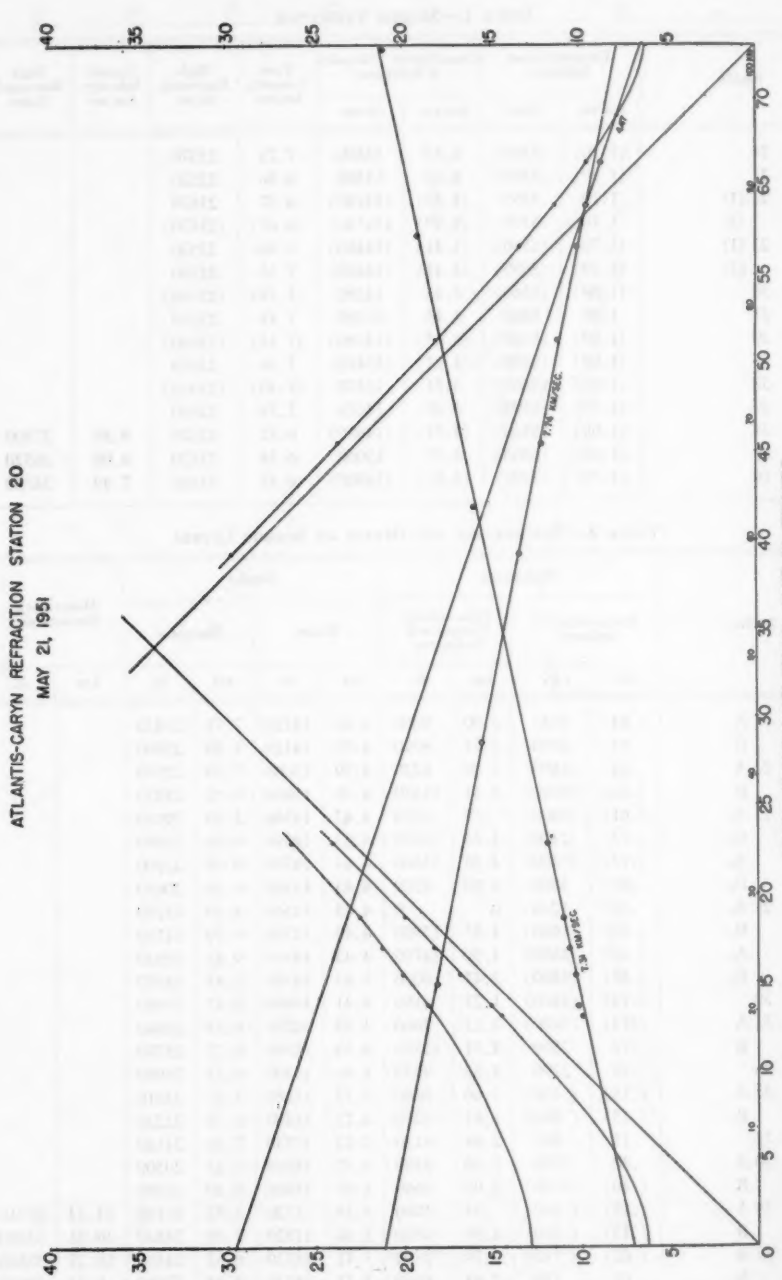


FIGURE 10.—ATLANTIS 172—CARYN 22 PROFILE 20

TRAVEL TIME IN SECONDS

Profile

26 A
B
25 A
B
4
5

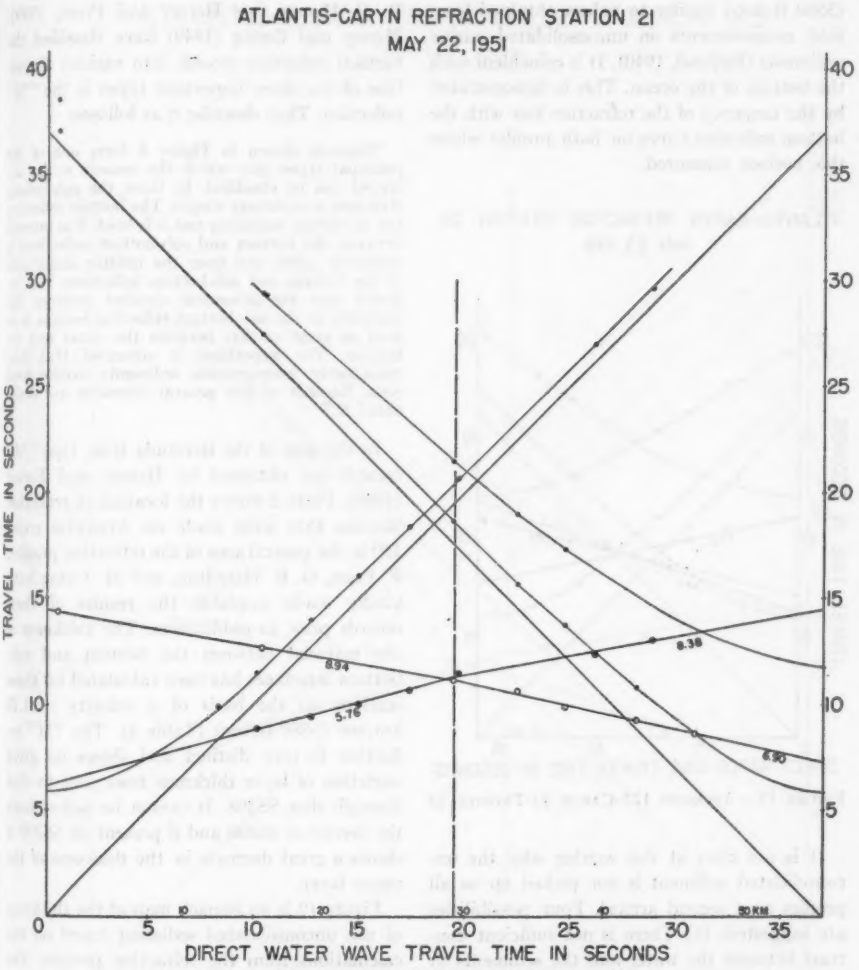


FIGURE 11.—ATLANTIS 172–CARYN 22 PROFILE 21

FIGURE 10.—ATLANTIS 172–CARYN 22 PROFILE 20

TABLE 3.—BERMUDA PROFILE

Profile	Depth of Water		Depth of Volcanic Platform		Velocity of Volcanic Basement	
	km	ft.	km	ft.	km/sec	ft/sec
26 A	.015	49	.082	268	5.34	17510
B	.015	49	.035	115		
25 A	.013	43	.089	291	5.13	16840
B	.013	43	.057	188		
4	.012	40	.072	235	(5.25)	(17220)
5	.012	40	.096	316	(5.25)	(17220)

used for the purpose of calculation on unreversed profiles or on those profiles in which a particular refraction horizon was not measured. The velocities given on the travel-time graphs (Figs. 4–15) are the apparent velocities for the specified lines.

IDENTIFICATION OF REFRACTION LAYERS

The low-velocity layer is identified as the unconsolidated sediments at the bottom of the ocean. It has an average velocity of 1.70 km/sec

(5580 ft/sec.) similar to values obtained from field measurements on unconsolidated marine sediments (Heiland, 1940). It is coincident with the bottom of the ocean. This is demonstrated by the tangency of the refraction line with the bottom reflection curve on both profiles where this horizon measured.

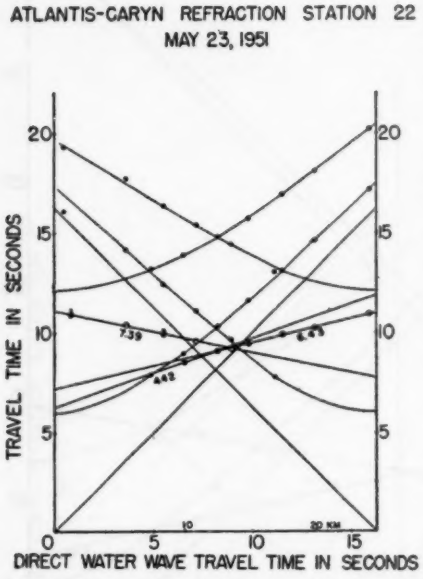


FIGURE 12.—ATLANTIS 172–CARYN 22 PROFILE 22

It is not clear at this writing why the unconsolidated sediment is not picked up on all profiles as a second arrival. Four possibilities are suggested: (1) There is not sufficient contrast between the water and the sediments in all areas. (2) The boundary between the sediments and the water is not sharp enough to allow a distinct refraction to result. (3) There is considerable layering in the sediments themselves, and/or (4) The layer is too thin in comparison with the horizontal distances involved.

A second important method of investigating the sub-bottom structure is by the use of seismic reflection records. Some of the first records obtained in the Atlantic Ocean basin are described by Hersey and Ewing (1949). Since then, over 3000 more records have been taken, principally by J. B. Hersey, F. Press, and B. C. Heezen (*see* Hersey and Press, 1949). Hersey and Ewing (1949) have classified the vertical reflection records into various classes. One of the more important types is the "M" reflection. They describe it as follows:

"Records shown in Figure 4 form one of the principal types into which the records so far observed can be classified. In these the sub-bottom structure is extremely simple. The bottom reflection has an abrupt beginning and it is brief. The interval between the bottom and sub-bottom reflections is relatively quiet, and from the relative amplitudes of the bottom and sub-bottom reflections is it inferred that the acoustical contrast between the materials at the sub-bottom reflecting horizon is at least as great as that between the water and the bottom. The hypothesis is advanced that here remarkably homogeneous sediments overlie hard rock. Records of this general character are designated N."

In the area of the Bermuda Rise, type "M" records are obtained by Hersey and Ewing (1949). Plate 2 shows the location of reflection stations that were made on ATLANTIS cruise 150 in the general area of the refraction profiles. F. Press, G. R. Hamilton, and M. Ewing have kindly made available the results of these records prior to publication. The thickness of the material between the bottom and sub-bottom interfaces has been calculated for these stations on the basis of a velocity of 1.70 km/sec (5580 ft/sec) (Table 4). The "M" reflection is very distinct and shows no great variation of layer thickness from shot to shot through shot SS298. It cannot be picked from the record of SS300 and if present on SS299 it shows a great decrease in the thickness of the upper layer.

Figure 19 is an isopach map of the thickness of the unconsolidated sediment based on the calculations from the refraction profiles. The similarity between the isopach map of the refraction data and the thickness calculations in Table 4 from the reflection data is striking and gives a positive identification of the "M" horizon as the bottom of the unconsolidated sediments. The refraction results show the thickness increasing up to .75 km. (2500 ft.) in the depression near Bermuda but generally varying from .45 km. (1500 ft.) in the central portion of the Bermuda Rise to less than .15 km. (500 ft.) north of the Nares Basin. The reflection records show the thickness varying from .30–.45 km. (1000–1500 ft.) in the central por-

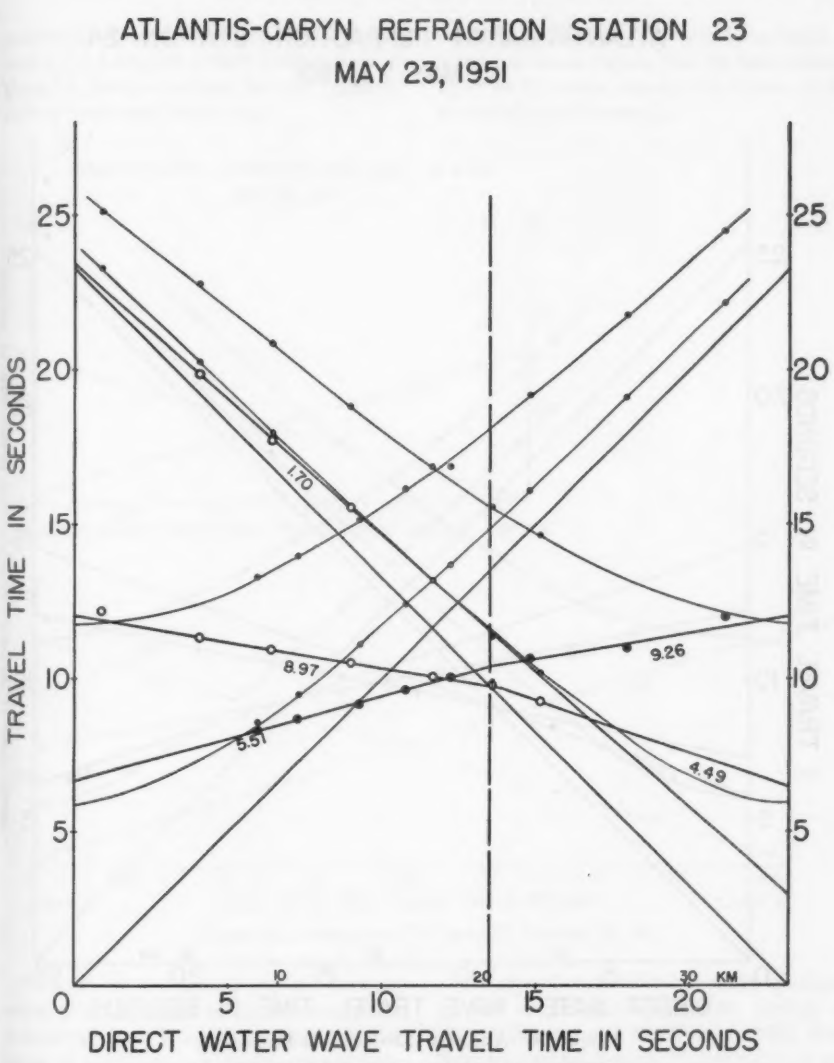


FIGURE 13.—ATLANTIS 172–CARYN 22 PROFILE 23

tion of the Bermuda Rise to .06–.20 km. (200–700 ft.) north of the Nares Basin.

Besides picking up vertical reflection measurements of this horizon from ATLANTIS #150 data, CARYN #22 obtained wide-angle reflections from the same horizon on her refraction records. Sample records of each cruise are shown in Plate 4.

If it can be demonstrated that the "M" horizon corresponds to the bottom of the unconsolidated sediments in general and not just in particular to the Bermuda Rise area, it will become a powerful tool for investigating the thickness of the unconsolidated sediment over those parts of the ocean bottom where these sediments are sufficiently homogeneous to

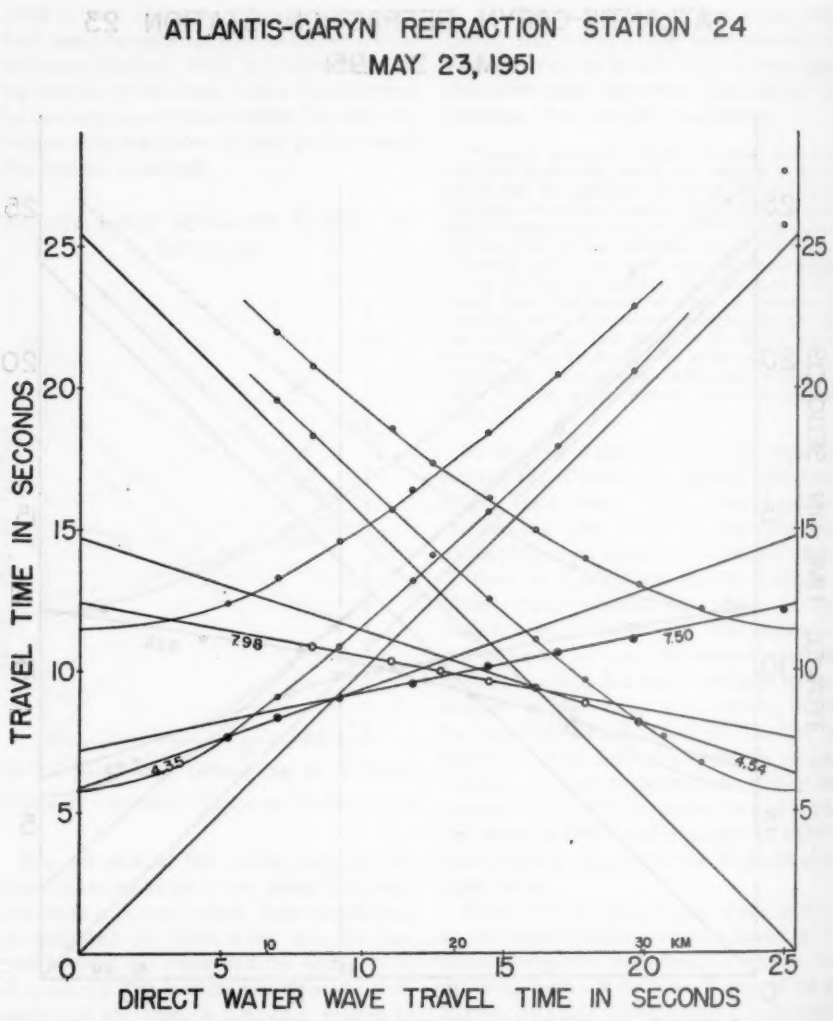


FIGURE 14.—ATLANTIS 172–CARYN 22 PROFILE 24

permit clear identification of the "M" horizon. Vertical reflection records can be taken much more easily than refraction records. They require less time and personnel and only one ship. The measurements can be made while the ship is underway so that a larger area can be covered in the same time than by the refraction method.

The intermediary layer is identified as consolidated volcanics and sediments. It has an average velocity of 4.51 km/sec (14790 ft/sec) and lies beneath the unconsolidated sediment. It is harder to give a positive identification to this layer, and the identification comes for the most part from its seismic velocity. It is extremely doubtful that this layer is granitic. Leet and Ewing (1932) obtained values ranging from 4.96–5.08 km/sec (16260–16670 ft/sec) for the Quincy, Massachusetts; Rockport, Massachusetts; and Westerly, Rhode Island granites. Similar velocities have been obtained for other

granites by other investigators. Values ranging from 5.2–5.8 km/sec (17000–19000 ft/sec) are given by various workers for the "granitic" layer of continental seismology.

considerable portion of pyroclastic material. A priori one would expect that the intermediary layer would consist mainly of volcanics in the neighborhood of Bermuda.

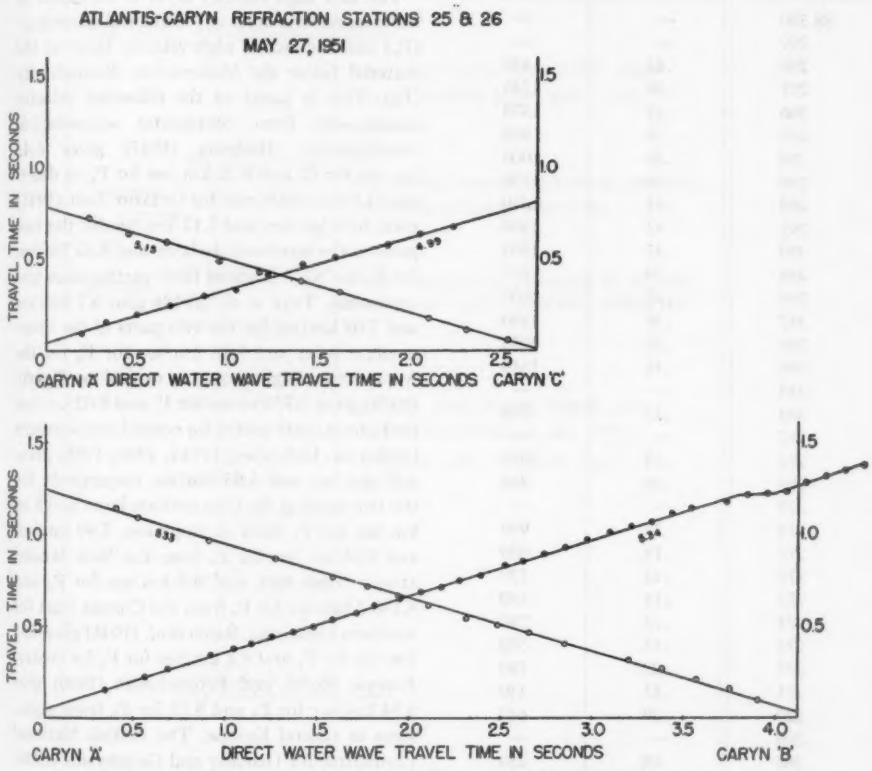


FIGURE 15.—ATLANTIS 172–CARYN 22 PROFILE 25, 26

From the information from seismic measurements, it is impossible to decide whether the consolidated layer is made up of lithified sediments, or volcanics, or a combination of both. The velocity of 4.51 km/sec (14790 ft/sec) is in the range of values obtained for limestones and shales. The velocity for the rocks of the volcanic platform of Bermuda was found to be 5.25 km/sec (17220 ft/sec.). From this measurement and from various published data (Heiland, 1940), it is clear that the measured velocity is too low for any massive igneous rock. If this layer is volcanic in origin, it must contain a

The type of material and structure envisaged is that of the observed surface geology of Hawaii (Stearns and MacDonald, 1946). Here there are alternate beds of lithified sediment and pyroclastics with numerous lava flows. Raitt (1951) found a similar seismic layer in the submarine mountain range west of the Hawaiian Islands. He considers that it is volcanic in origin, on the basis of measurements on known volcanic rocks in the vicinity of the Hawaiian Islands. Additional evidence for the identification of this layer comes from the fact that pebbles of volcanic origin have been found in cores in the general area of the profiles.

TABLE 4.—THICKNESS OF "M" LAYER

Shot No.	Thickness	
	km	ft.
SS 300	—	—
299	—	—
298	.43	1430
297	.38	1240
296	.42	1370
295	.28	910
294	.30	1000
293	.34	1120
292	.44	1450
291	.42	1390
290	.37	1200
289	.19	610
288	.33	1100
287	.36	1190
286	.32	1070
285	.44	1440
284	—	—
283	.23	770
282	—	—
281	.33	1070
280	.26	860
279	—	—
278	.29	950
277	.18	600
276	.22	720
275	.14	450
274	.23	740
273	.15	510
272	.22	740
271	.13	430
270	.20	640
269	—	—
268	.08	250
267	.12	400
266	.12	400
265	.09	280
264	.15	500
263	.18	580
262	.09	280
261	.16	510

It was explained in the discussion of the individual profiles that two types of deep structure were found. Over the Bermuda Rise only one high-velocity layer was found while, over the northern part of the Nares Basin, two high-velocity horizons were determined. The first of these horizons over the Nares Basin had an average velocity of 6.63 km/sec (21750 ft/sec) at a depth of 7.01 km. (23000 ft.) and the second an average velocity of 8.03 km/sec (26350 ft/sec) at a depth of 9.94 km. (30970 ft.). (Hersey *et al.* (1951) obtain a similar structure in the southern part of the Nares Deep.)

The first high-velocity layer is identified as the intermediate layer of continental seismology (P_y) and the second high-velocity layer as the material below the Mohorovicic discontinuity (P_n). This is based on the following velocity comparisons from continental seismological investigations. Hodgson (1947) gives 6.45 km/sec for P_y and 8.20 km/sec for P_n as determined from rockbursts for Ontario. Leet (1941) gives 6.77 km/sec and 7.17 km/sec for the two parts of the intermediate layer and 8.43 km/sec for P_n for New England from earthquakes and explosions. Tuve *et al.* (1948) give 6.7 km/sec and 7.05 km/sec for the two parts of the intermediate layer and 8.15 km/sec for P_n for the Appalachian Highlands from explosions. Byerly (1939) gives 6.72 km/sec for P_y and 8.02 km/sec for P_n from earthquakes for central and southern California. Gutenberg (1944; 1946; 1951) gives 6.05 km/sec and 6.95 km/sec respectively for the two parts of the intermediate layer and 8.06 km/sec for P_n from earthquakes, 7.99 km/sec and 8.04 km/sec for P_n from the New Mexico atomic bomb test, and 6.5 km/sec for P_y and 8.1–8.2 km/sec for P_n from the Corona blast for southern California. Reich *et al.* (1948) give 6.55 km/sec for P_y and 8.2 km/sec for P_n for central Europe. Rothé and Peterschmitt (1950) give 6.54 km/sec for P_y and 8.15 for P_n from explosions in central Europe. The British National Committee for Geodesy and Geophysics (1946) gives 8.10 km/sec for P_n for North Germany. If the intermediate layer is considered to be made up on one seismic part, the first high-velocity basement (6.63 km/sec) corresponds with that layer. If the intermediate layer is considered to be made up of two parts, the first high-velocity basement corresponds with the upper part of that layer. The second high-velocity basement corresponds in velocity with the material below the Mohorovicic.

Over the Bermuda Rise, only one high-velocity layer was determined. This layer has an average velocity of 7.19 km/sec, intermediate between the values found for the two horizons in the Nares Basin.

There are no field measurements of seismic velocities on known rocks which are as high as

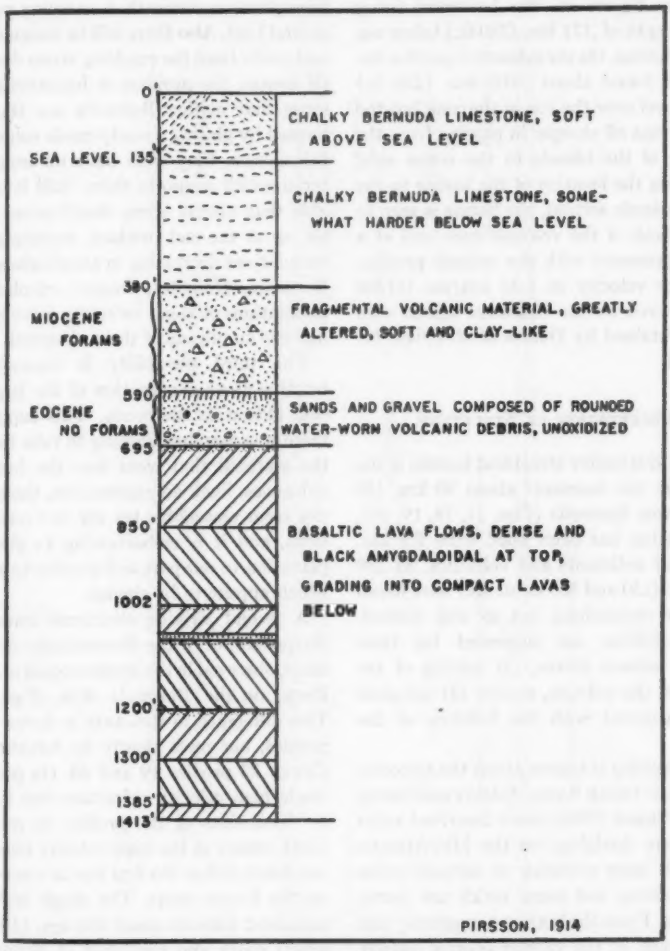


FIGURE 16.—SECTION OF PIRSSON BORING

the ones measured for the basement of the Nares Basin and Bermuda Rise. Leet (1933) gives 6.22 km/sec for the Surbury norite. Hughes and Jones (1950) have made high frequency measurements on small samples immersed in oil and obtain a velocity of 6.81 km/sec for norite (hypersthene gabbro) at a pressure of 6.86 km. (3750 fathoms) of water and a temperature of 32° C. The velocities that they obtained for their other samples, viz, andesite, quartz monzonite, granite, and diorite, were considerably lower at the same temperature and pressure. This gives little data to correlate the measured velocities with a rock type, but it indicates that the rock is a basic, heavy mineral, undersaturated type. This agrees with the oceanic olivine-basalt parent magma association, deduced from the petrographic evidence of the rocks of the Mid-Atlantic Ridge described by Shand (1949), and the associated islands, reviewed by Turner and Verhoogen (1951).

The identification of the Bermuda island basement is quite easy. It is the truncated cone of the Bermuda volcanoes. A deep boring was made on Hamilton Island which penetrated the basement. Pirsson (1914) describes the section

as shown in Figure 16, the basement being found at a depth of .171 km. (560 ft.) below sea level in the boring. On the refraction profiles the basement is found about .076 km. (250 ft.) below sea level over the top of the cone, but the basement drops off sharply in passing from the lagoon side of the islands to the ocean side. Extrapolating the location of the boring to the line of the seismic section, the boring is seen to be on the flank of the volcanic cone and at a depth in agreement with the seismic profiles. The average velocity of 5.25 km/sec (17220 ft/sec) observed for the basement agrees with the value obtained by Dobrin *et al.* (1949) for Bikini Atoll.

Interpretation of Structure

The most distinctive structural feature is the depression in the basement about 90 km. (50 naut. mi.) from Bermuda (Figs. 17, 18, 19, 20). This depression has been filled with 5.5 km. (18000 ft.) of sediments and volcanics. At 280 and 560 km. (150 and 300 naut. mi.) were found two smaller depressions, not as well defined. Three possibilities are suggested for their origin: (1) tectonic forces, (2) loading of the basement by the volcano, and/or (3) marginal sinking concurrent with the building of the volcano.

Next to nothing is known about the tectonics in the Atlantic Ocean Basin. Tolstoy and Ewing (1949) and Shand (1949) have described rocks obtained from dredgings on the Mid-Atlantic Ridge which show evidence of mylonitization and slickensiding and some which are partly fault breccia. From the bottom topography and from the rocks on the various oceanic islands, several guesses have been made as to the tectonics that have occurred in the Atlantic Ocean Basin. It is entirely possible that undulations of the basement such as those observed southeast of Bermuda, particularly the outer two, are common over a large part of the Atlantic Ocean Basin; but the proof cannot be made from the evidence of this one area.

Gunn (1943a; 1943b) calculated the effect of loading the lithosphere with an exponential load and derived for the Hawaiian Islands the resultant structure and stress distribution. In this case, a slight depression on the margin of the load will result from the fact that the rigid lithosphere underneath is carrying part of the central load. Also there will be secondary basins and swells from the resulting stress distribution. Of course, his problem is hypothetical in the sense that neither Bermuda nor Hawaii were formed by placing a ready-made volcano on the lithosphere; they were built up from the material which supports them. Still it is conceivable that similar stress distributions might be set up as the end product, causing a series of undulations decreasing in amplitude away from Bermuda. However, Gunn's calculations give undulations of about twice the wave length and half the amplitude of those observed.

The third possibility is immediately attractive as an explanation of the large depression closest to Bermuda. This supposes that there was marginal sinking to take the place of the material that went into the formation of volcanoes. Such an explanation, though, would not seem reasonable for the two outer depressions, and it is embarrassing to give one explanation to one part and another to other parts which appear to be similar.

A second striking structural feature is the disappearance of the discontinuity in the basement, observed in the northern part of the Nares Deep, on the Bermuda Rise (Figs. 17, 18). This difference in structure is shown by all the profiles, but most clearly by Atlantis #172-Caryn 22 profiles 19 and 20. On profile 20, a single high-velocity refraction line is obtained for both sides of the profile; on profile 19, a break occurs in the high-velocity line, and it is possible to follow the first line as a second arrival on the longer shots. The single high-velocity basement extends about 410 km. (220 nautical miles) south and southeast of Bermuda. This boundary does not correspond exactly with the topographic limits of the Bermuda Rise (Tolstoy, 1951). Whether the single-velocity basement represents an intrusive activity associated with the Bermuda volcanoes and is the mixing of the two discrete layers measured over the Nares Basin or whether it is a primary feature of basement structure and the possible cause for the location of Bermuda volcanoes cannot be answered. It is our opinion that, in the Bermuda Rise region, there is a gradual change in velocity to a value of 8.0–8.4 km/sec associated with the material below the Mohorovicic discontinuity, this range of values being ob-

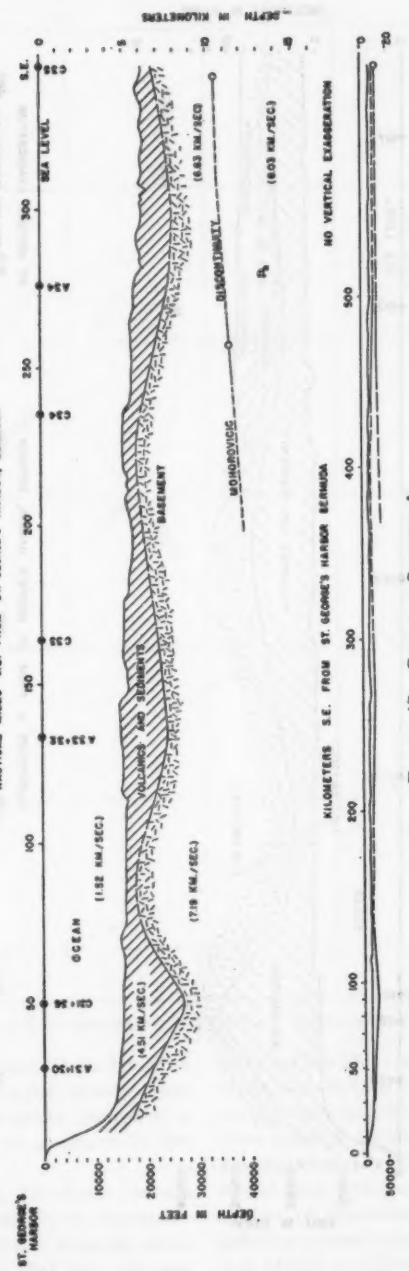


FIGURE 17.—GEOLOGIC SECTION A

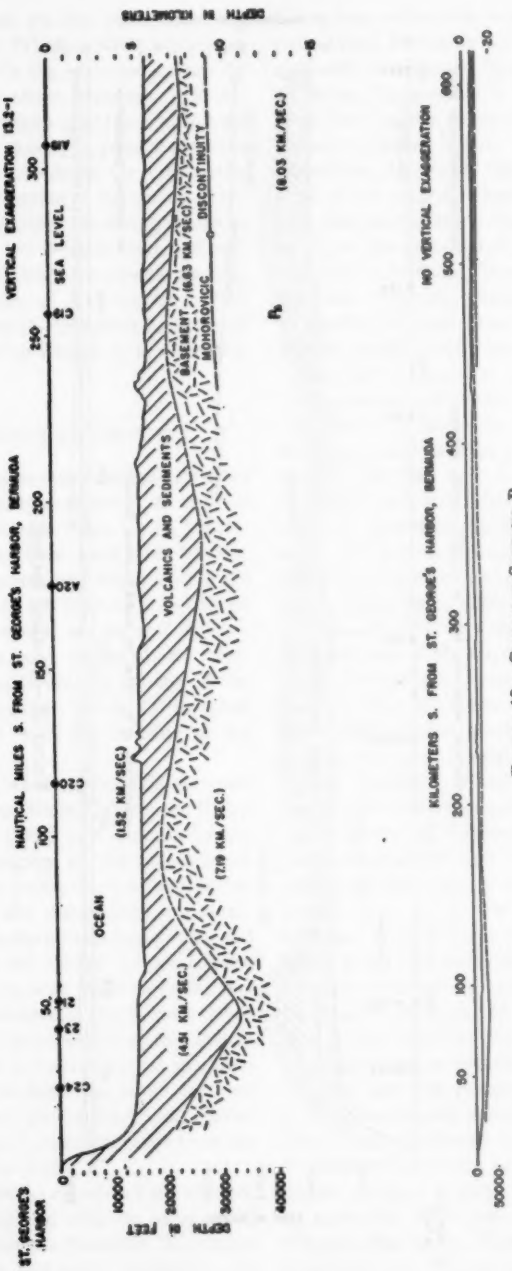


FIGURE 18.—GEOLOGIC SECTION B

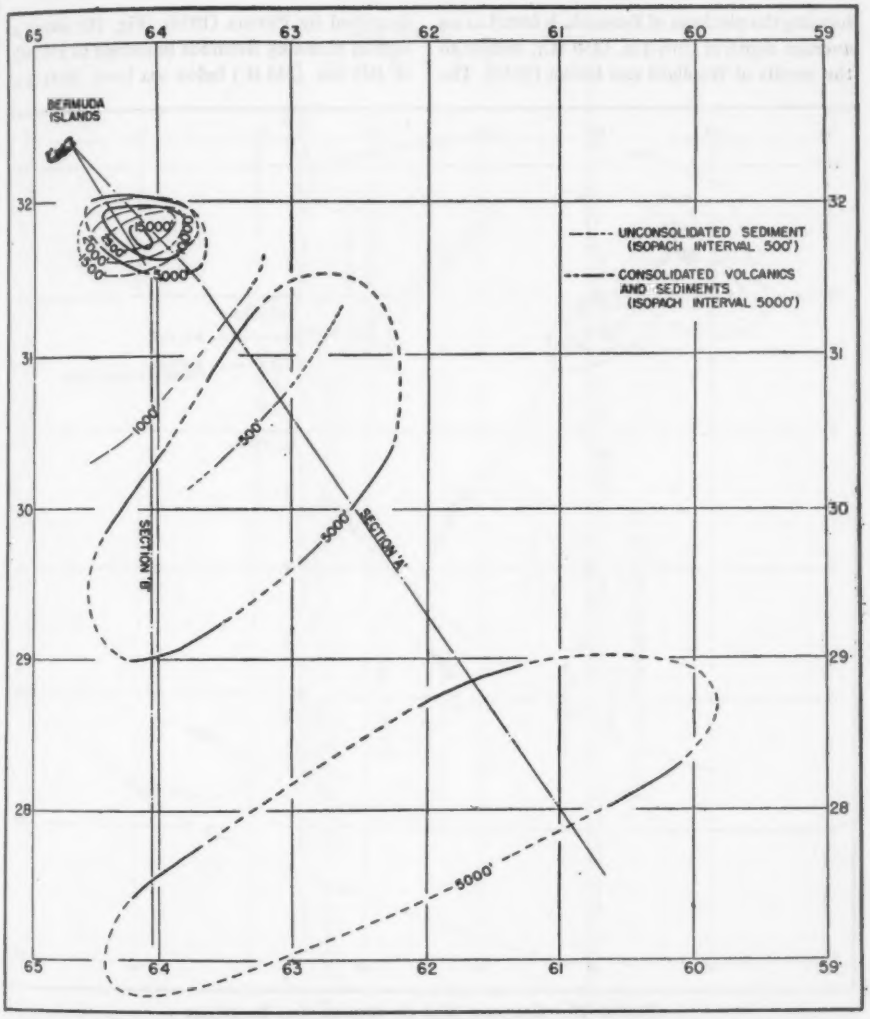


FIGURE 19.—ISOPACH MAP OF UNCONSOLIDATED SEDIMENT AND CONSOLIDATED VOLCANICS AND SEDIMENTS

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The isopach map (Fig. 19) shows the unconsolidated sediments thick in the depression near Bermuda and gradually thinning away from Bermuda, indicating that Bermuda was the source of those sediments. Supporting evidence for this idea comes from one of the cores of ATLANTIS #164 in which recent shallow water mollusc shells were found at a depth of 5.4 km (2400 fathoms) (Ericson *et al.*, 1952) and from the mineralogical analysis by Young (1939) of several short cores from the Bermuda Rise. The method of deposition is thought to be by turbidity current action as described by Ericson *et al.* (1952) and Kuenen (1950).

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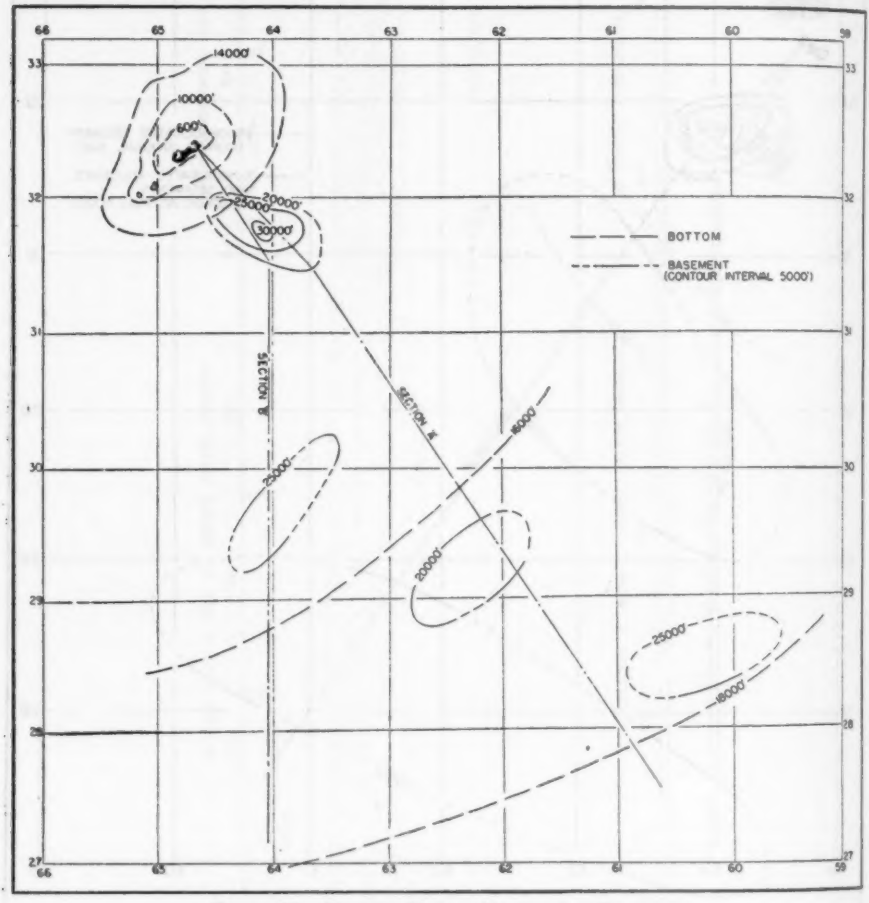

FIGURE 20.—CONTOUR MAP OF BOTTOM AND BASEMENT

platform drops off to the flank of the volcanoes in passing from the lagoon to the ocean side of the islands (Fig. 21). This puts the boring described by Pirrson (1914) on the flank of the volcanoes, and the depth of basement observed in the boring .171 km. (560 ft.) below sea level is consistent with the refraction results. Sayles (1931) gives a geologic history of the Pleistocene in terms of the eolianites (glacial), fossil soils (interglacial), and marine limestones of the surface geology of the islands. The boring formation of red oxidized material, consisting mainly of volcanic debris. Foraminifera in this formation identify it as Miocene at the top and Eocene at the bottom. Below this is an unoxidized formation of sands and gravels of volcanic debris to the basement of basaltic lava flows. Carman (1933) describes the foraminifera of the oxidized formation as predominantly Miocene with one specimen of the Eocene *Rotalia armata*.

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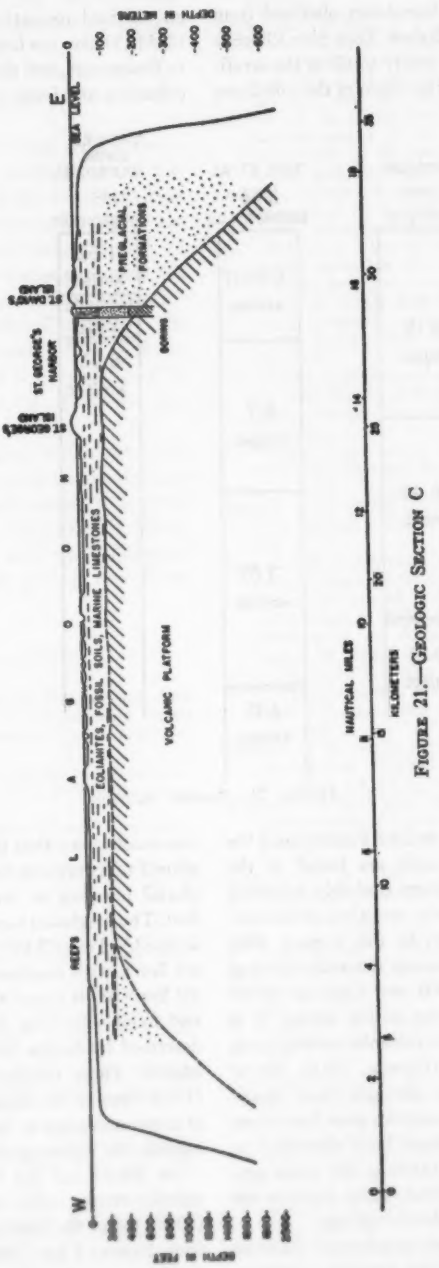

FIGURE 21.—GEOLOGIC SECTION C

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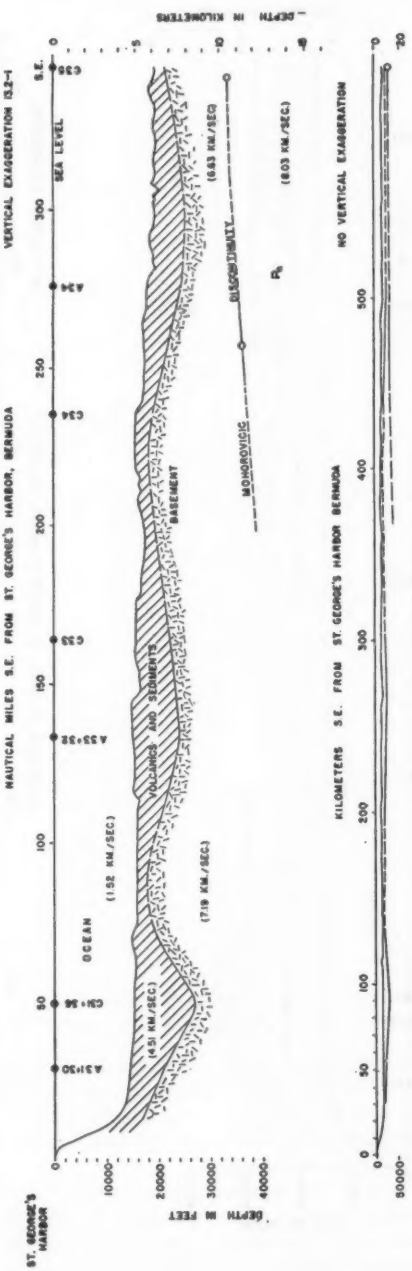

FIGURE 17.—GEOLOGIC SECTION A

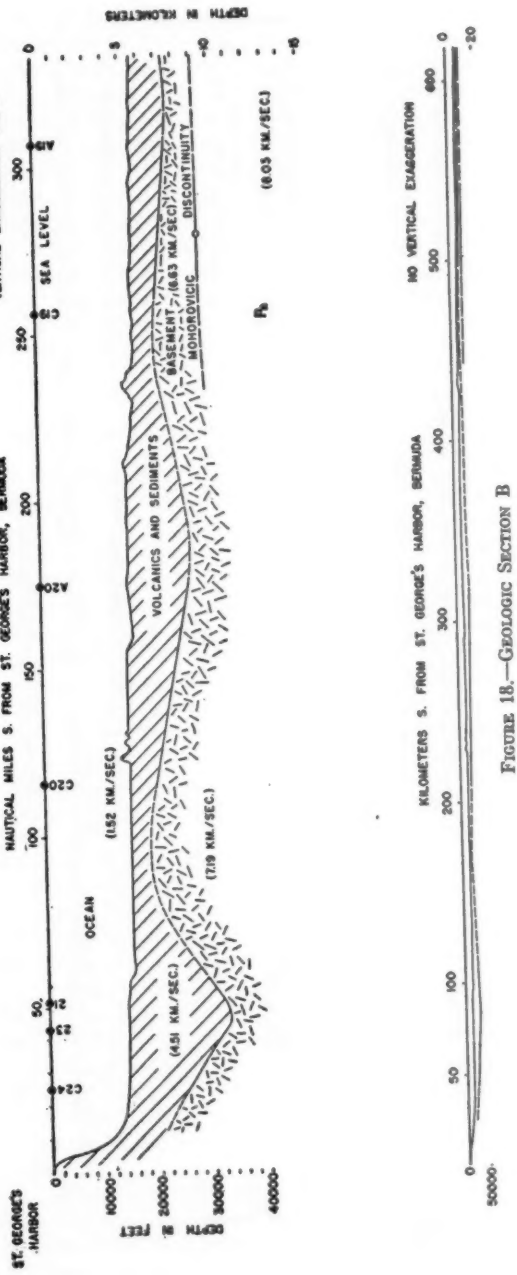

FIGURE 18.—GEOLOGIC SECTION B

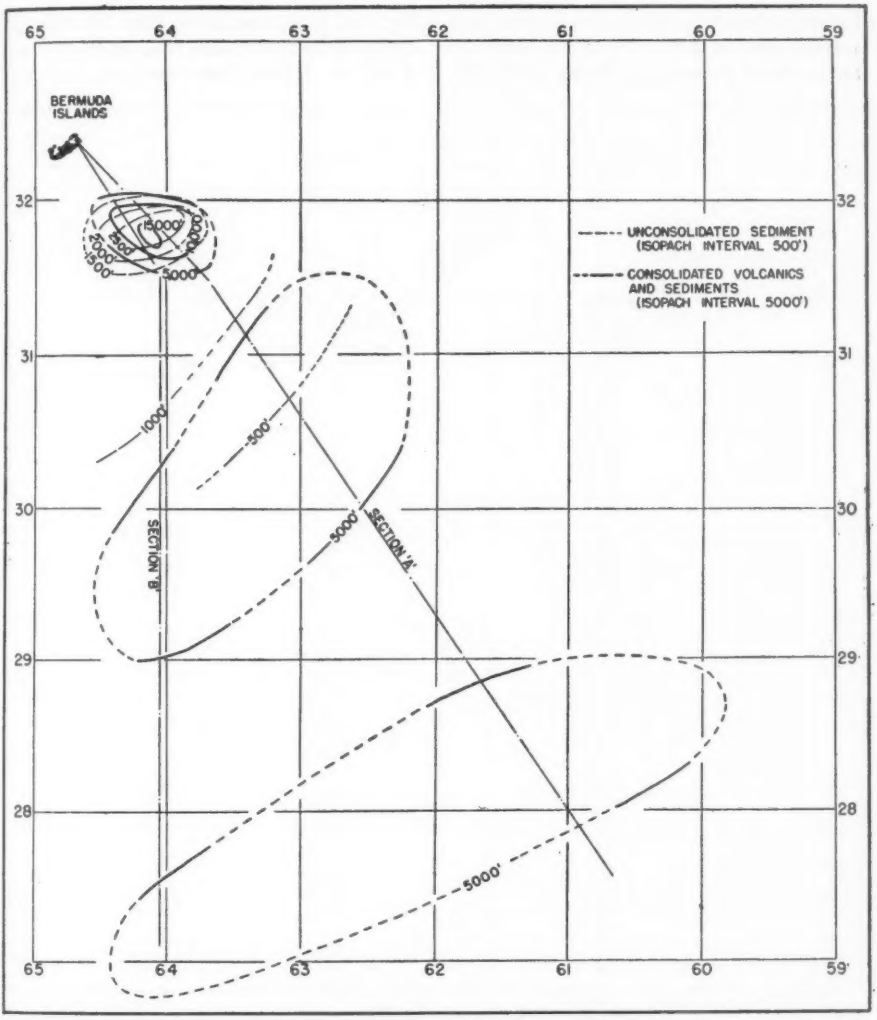

FIGURE 19.—ISOPACH MAP OF UNCONSOLIDATED SEDIMENT AND CONSOLIDATED VOLCANICS AND SEDIMENTS

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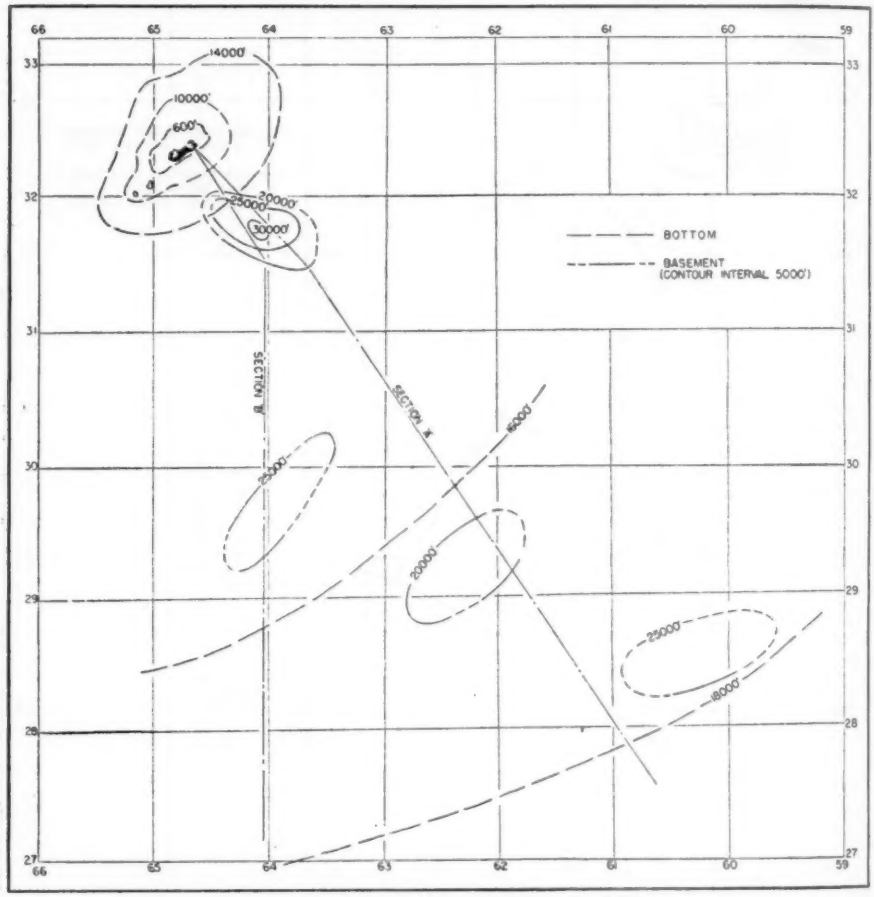

FIGURE 20.—CONTOUR MAP OF BOTTOM AND BASEMENT

platform drops off to the flank of the volcanoes in passing from the lagoon to the ocean side of the islands (Fig. 21). This puts the boring described by Pirrson (1914) on the flank of the volcanoes, and the depth of basement observed in the boring .171 km. (560 ft.) below sea level is consistent with the refraction results. Sayles (1931) gives a geologic history of the Pleistocene in terms of the eolianites (glacial), fossil soils (interglacial), and marine limestones of the surface geology of the islands. The boring formation of red oxidized material, consisting mainly of volcanic debris. Foraminifera in this formation identify it as Miocene at the top and Eocene at the bottom. Below this is an unoxidized formation of sands and gravels of volcanic debris to the basement of basaltic lava flows. Carman (1933) describes the foraminifera of the oxidized formation as predominently Miocene with one specimen of the Eocene *Rotalia armata*.

Moore and Moore (1946) describe a sequence

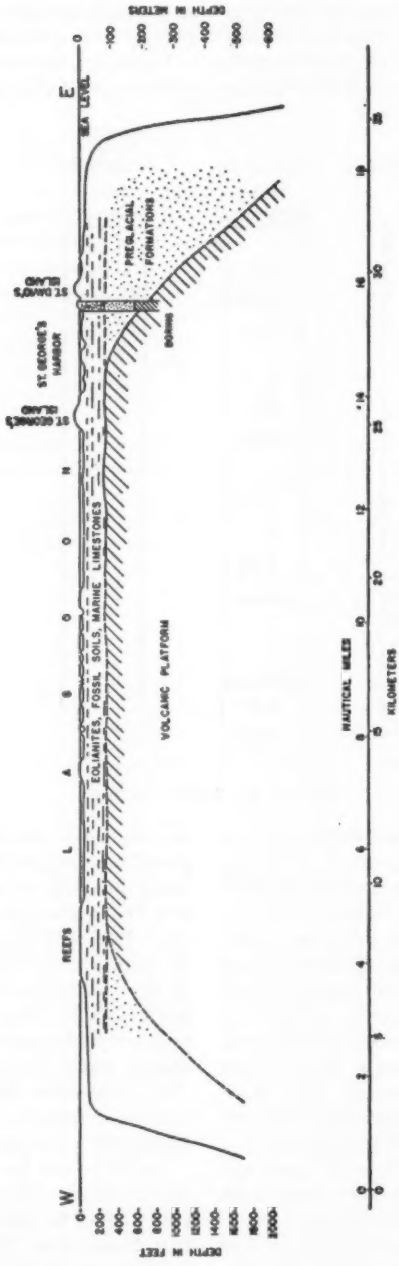

FIGURE 21.—GEOLOGIC SECTION C

of sands, clays, and limestones obtained from dredgings in Castle Harbor. They give Pliocene age to these deposits, solely to fill in the stratigraphic gap between the origin of the volcanoes

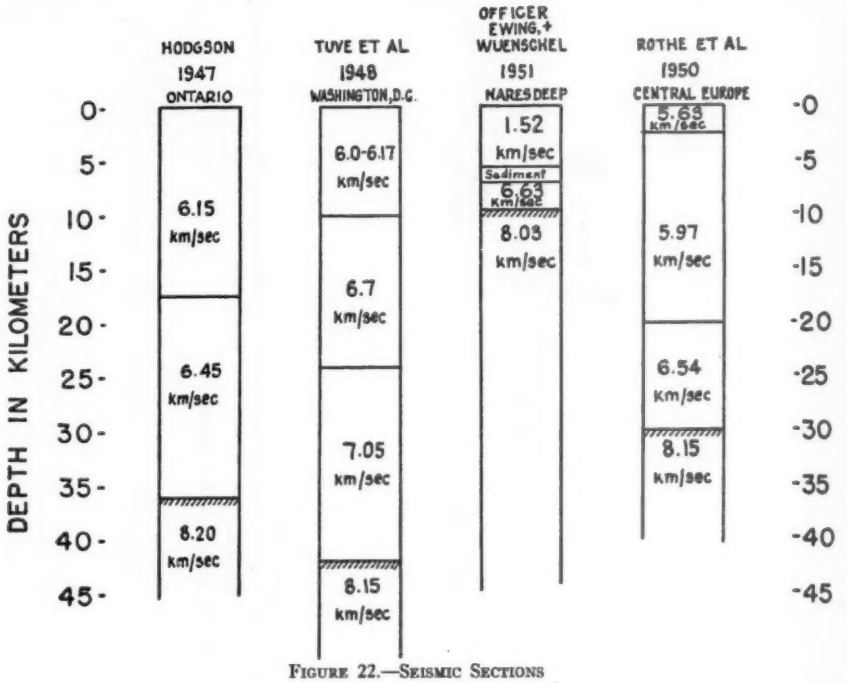

FIGURE 22.—SEISMIC SECTIONS

which they believed to be late Tertiary and the Pleistocene. All the fossils are found in the Recent. Further they were probably incorrect in defining the age of the eruption of the volcanoes as late Tertiary. In this respect, they ignored the foraminiferal age determinations of Cushman (Pirsson, 1914) and Carman (1933) on the oxidized formation of the boring. It is more probable that the volcanic activity took place in the Triassic (Pirsson, 1914). About two-thirds of the way through their stratigraphic sequence is a mangrove peat. Logs from this mangrove swamp have been identified by Kulp (1951) as formed 11500 ± 700 years ago, i.e., of Mankato age. Thus, these deposits are of Pleistocene to Post-pleistocene age.

All the geological and geophysical data on Bermuda, the depth of the volcanic platform, the depth of the oxidized formation, that such an oxidized formation is present at .075 km. (245 ft.) below sea level and that it is of Miocene to Eocene age, and the Pleistocene history of the eolianites and fossil soils on the islands, lead to one conclusion—that the volcanic platform was planed to its present depth during a Pleistocene glacial lowering of sea level, presumably the first. The preglacial formations were removed to a base-level of .075 km. (245 feet) below present sea level, with maximum relief of the order of .03 km. (100 ft.); and the Pleistocene eolianites and fossil soils were deposited in the manner described by Sayles (1931) to form the present islands. These conclusions agree with Daly's (1910) ideas on the effects of glaciation on atolls. It is not necessary to hypothesize subsidence to explain the known geology of Bermuda.

On Bikini and the Virgin Islands, different seismic results were obtained. Dobrin *et al.* (1949) found the basement at a depth varying from 2 km to 4 km (7000 ft. to 13000 ft.) below sea level on Bikini, and Worzel and Ewing (1948) found the basement horizontal at depths

of .5 km and .4 km (1700 ft. and 1400 ft.) below sea level on the north and south sides respectively of the Virgin Islands.

Seismology

Figure 22 shows the striking differences in seismic structure of the crustal layers of the Atlantic Ocean Basin and the bordering continents. Sections of the eastern part of North America on the one side and Central Europe on the other are included for comparison with the Nares Basin section. There is no "granitic" (sialic) layer present under the ocean. The intermediate layer is extremely thin, and the Mohorovicic discontinuity is at a depth of 10 km as contrasted with 40 km. under the continents.

Raitt (1949; 1951) obtains a similar structure for the Pacific Ocean Basin so that there appears to be no difference in seismic structure between the Atlantic and Pacific Ocean Basins. These results are in agreement with the earthquake surface wave studies of Ewing and Press (1950; 1951).

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LAMONT GEOLOGICAL OBSERVATORY, PALISADES, NEW YORK.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, OCTOBER 5, 1951.

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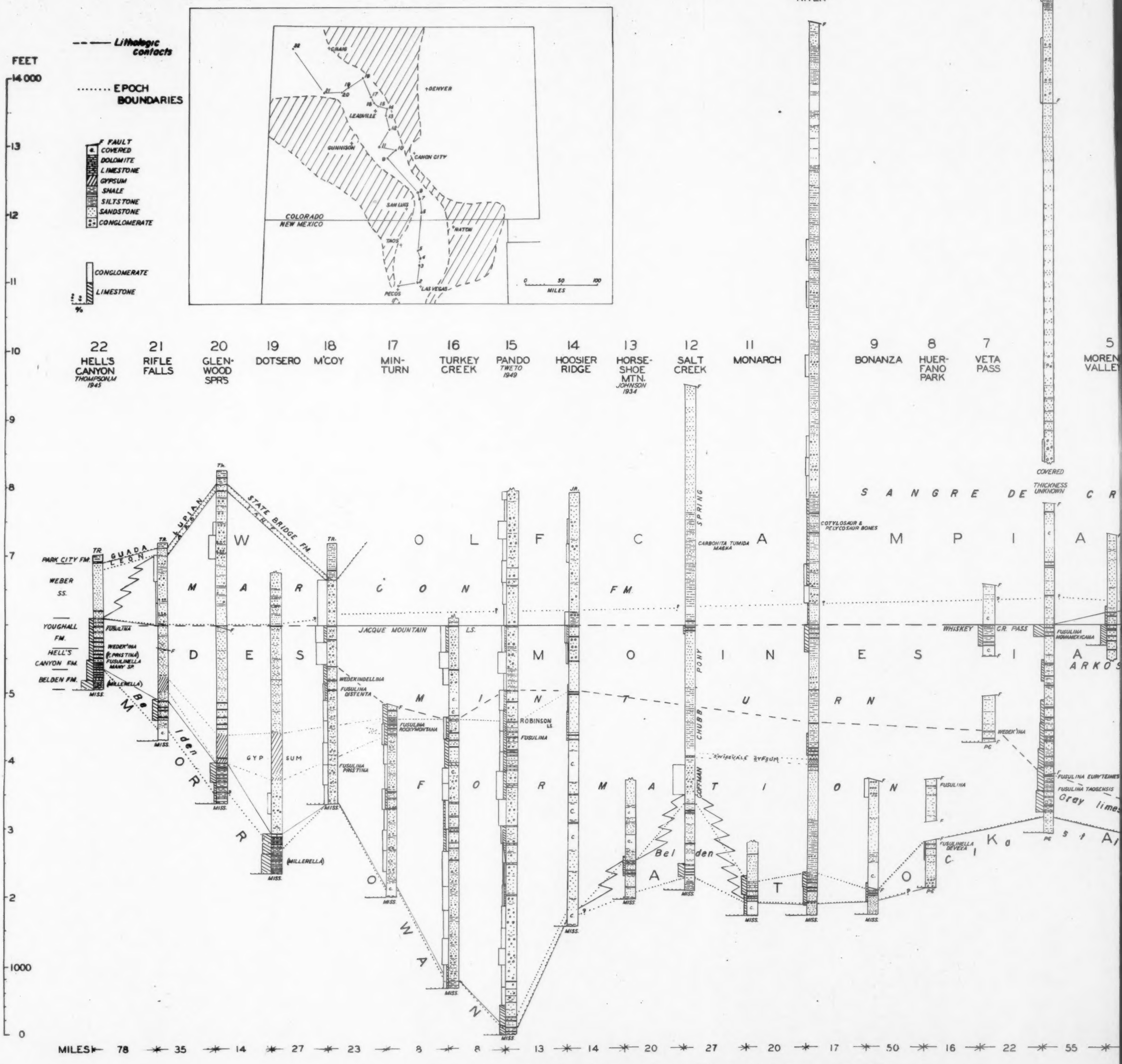
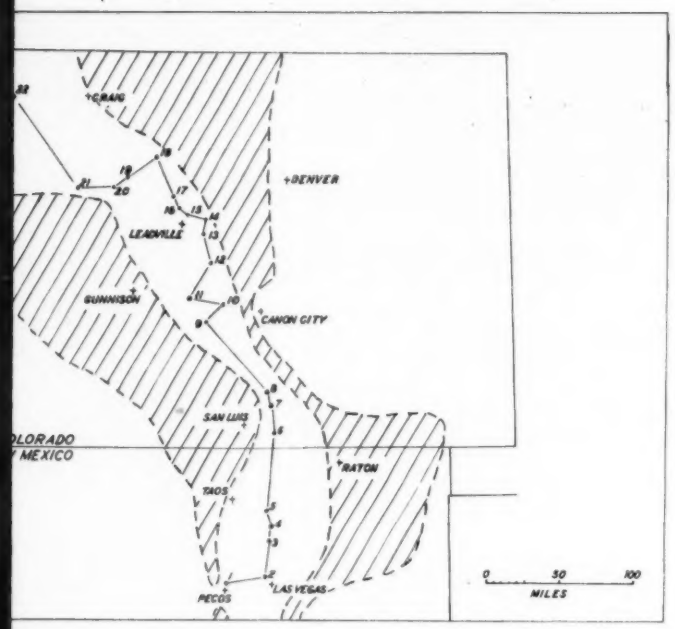


STRATIGRAPHIC COLUMNS OF PERMO-PENNSYLVANIAN STRATA IN THE TROUGH

Lithologic units are delineated by solid lines of correlation; time equivalence is indicated by dotted lines. Datum plane Jacque Mountain-Whiskey Creek Pass limestones or their equivalent.



10 ARKANSAS RIVER

6 WHISKEY CREEK PASS

18 M'COY | 17 MIN-TURN | 16 TURKEY CREEK | 15 PANDO *TWETO 1949* | 14 HOOSIER RIDGE | 13 HORSE-SHOE MTN. *JOHNSON 1934* | 12 SALT CREEK | 11 MONARCH | 9 BONANZA | 8 HUER-FANO PARK | 7 VETA PASS | 5 MORENO VALLEY | 4 COYOTE CREEK | 3 MORA RIVER | 2 GALLINAS RIVER | 1 PECOS

27 — 23 — 8 — 8 — 13 — 14 — 20 — 27 — 20 — 17 — 50 — 16 — 22 — 55 — 13 — 15 — 22 — 22 — MILES

STRATIGRAPHIC COLUMNS OF PERMO-PENNSYLVANIAN STRATA IN THE TROUGH

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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PP. 809-880, 5 FIGS., 3 PLS. AUGUST 1952

STRATIGRAPHY IN THE PERMO-PENNSYLVANIAN ZEUGOGEOSYNCLINE OF COLORADO AND NORTHERN NEW MEXICO

By Kenneth G. Brill, Jr.

Abstract

The Permo-Pennsylvanian zeugogeosyncline of Colorado and northern New Mexico, unique among the troughs of the western United States, was a rapidly subsiding basin with highlands on both sides.

Its development was progressive. The Morrow strata were deposited in the northern half of the trough. Following the retreat of the Morrow sea, the Atoka sea entered the southern part of the trough. This sea remained until Desmoinesian time, and the Atoka and Desmoines faunas are mixed. Marine sedimentation reached a climax in Cherokeean time when a seaway traversed the length of the trough. In later Permo-Pennsylvanian time, the sea was confined to the ends of the trough, but thick deposits of nonmarine sediment accumulated in the center of the trough. Upper Pennsylvanian or Wolfcamp strata are several thousand feet thick.

Four principal lithologic units can be recognized: (1) the Belden and Kerber formations of Morrowan, Atokan, and possibly Desmoinesian age; (2) the Clastic member of the Sandia formation of Atokan age; (3) the Minturn and Madera formations, mainly of Cherokeean age; and (4) the Maroon and Sangre de Cristo formations, late Pennsylvanian or Wolfcampian in age. Four minor lithologic units occur at the ends of the trough: (1) the Yeso formation of Leonardian age; (2) the San Andres formation of Permian age; (3) the Weber sandstone of Pennsylvanian and Permian (?) age; and (4) the State Bridge formation of Guadalupian age.

The Jacque Mountain limestone of the Gore area may correlate with a bed which the writer has named the Whiskey Creek Pass limestone member of the Madera formation. If this correlation is correct, this layer can be used as a datum plane over much of the trough.

Cotylosaur and pelycosaur bones occur in the Sangre de Cristo formation in Fremont County, Colorado. These reptiles have not been found previously in this region.

CONTENTS

TEXT

	Page
Introduction	810
Acknowledgements	811
Previous nomenclature	811
Revised nomenclature	812
General statement	812
Mississipian or Pennsylvanian strata	812
Pennsylvanian strata	812
Belden formation	812
Clastic member of the Sandia formation	815
Madera and Minturn formation	816
Evaporite in the Minturn formation	820
Permian strata	821
Sangre de Cristo formation	821
Maroon formation	822
Yeso formation	822
Glorieta sandstone	823
Weber sandstone	823
State Bridge formation	823
Structural considerations	825
Discussion of areas	826
Northern New Mexico	826
Pennsylvanian	826
Permian (?)	827
Whiskey Creek Pass	828
Description	828
Pennsylvanian	828
Permian (?)	828
La Veta Pass	829
Pennsylvanian	829
Permian (?)	829
Huerfano Park	829
Pennsylvanian	829
Permian (?)	830
Red Canyon	831
Northern Sangre de Cristo	831
Arkansas River area	832
Description	832
Pennsylvanian	832
Permian (?)	834
Bonanza district	834
Red Gulch	835
Western South Park	835
Description	835
Pennsylvanian	835

	Page
Permian (?)	837
McCoy area	837
Description	837
Pennsylvanian	837
Permian	837
Faunal peculiarities	839
Geologic history	840
Pre-Pennsylvanian	840
Pennsylvanian	840
General statement	840
Morrowan time	840
Atokan time	841
Desmoinesian time	841
Missourian and Virgilian time	841
Wolfcampian time	841
Leonardian time	842
Guadalupian time	842
Conclusions	842
Detailed sections	843
Pecos section	843
Whiskey Creek Pass section	853
Arkansas River section	864
References cited	879

ILLUSTRATIONS

Figure	Page
1. Correlation chart showing the relative ages of formations in different parts of the trough	811
2. Morrowan paleogeography	813
3. Atokan paleography	816
4. Early Desmoinesian paleogeography	817
5. Isopach map of Weber, Lyons, and Glorieta sandstones in the vicinity of the Ancestral Rocky Mountains	824

Plate	Facing page
1. Stratigraphic columns of Permo-Pennsylvanian strata in the trough	809
2. Pre-Pennsylvanian paleogeology	812
3. Lithofacies and isopach map of Pennsylvanian strata between the Jacque Mountain-Whiskey Creek Pass limestone and the base of the section	818

Introduction

Numerous troughs and basins of sedimentation developed in the western United States during Pennsylvanian and Permian time. The zeugogeosyncline (Kay, 1947) of Colorado and northern New Mexico is unique in that it subsided relatively rapidly and had a landmass of considerable size on each side. Both landmasses contributed sediment to the subsiding basin.

The Paleozoic strata are exposed today in folds and fault blocks, so that considerable stratigraphic information can be obtained without subsurface methods. This is fortunate because few bore holes have been drilled in the region except near the ends of the trough.

Growth of the trough was progressive. During early Pennsylvanian time, the northern end was downwarped first, and the downwarping and filling extended southward as far as southern Colorado. During middle Pennsylvanian time, the southern and middle portions of the trough developed. The trough was completely flooded by the sea in Desmoinesian time, and sedimentation was continuous for more than 400 miles from Moffat County, Colorado, to Santa Fe County, New Mexico. It ranged in width from 20 to 100 miles and was probably narrowest in Custer and Huerfano counties, Colorado. It was bordered on the west by the Uncompahgre highland and on the east by the Front Range highland in Colorado and the Sierra Grande-Pedernal highland in New Mexico. In the areas of greatest subsidence, sediments accumulated to a thickness of nearly 13,000 feet.

The stratigraphic nomenclature has become voluminous in this region because outcrops are discontinuous, strata are mainly unfossiliferous, and changes of lithofacies are rapid. Different stratigraphic terms have been proposed in each district, and correlation between districts has been highly generalized. In spite of many local changes in facies, certain zones of limestone may be traced for several hundred miles, though individual beds may not be continuous. The Gray limestone member of the Madera formation is more or less continuous from central New Mexico to southern Colorado. Similarly the Jacque Mountain limestone and its probable equivalent, the Whiskey Creek Pass limestone, which occur higher in section can be traced over a much greater area.

The writer has spent 15 months in the field in this region. More than 40 detailed sections have been measured with a hand level. Earlier studies by the writer culminated in papers on the northern part of the trough (1942; 1944).

The present paper is an attempt to delineate the trough, to correlate the Pennsylvanian and Permian strata by means of lithologic characteristics and fauna, and to simplify the stratigraphic nomenclature.

Acknowledgements

A research grant from the Penrose Bequest of the Geological Society of America helped defray field expenses. Dr. J. Brookes Knight of the U. S. National Museum examined some of the gastropods from the Arkansas River section; Dr. Norman D. Newell of the American Museum of Natural History identified pelecypods from the Arkansas River and Salt Creek sections; Mrs. Betty Kellett Nadeau identified the ostracodes from the Arkansas River, Bonanza and Salt Creek sections; Dr. M. L. Thompson of the University of Wisconsin identified some of the fusulinids; Dr. J. M. Wilson of the University of Texas and Dr. T. E. White of the River Basin Surveys identified the reptile bones from the Arkansas River section; Dr. V. T. Allen of St. Louis University examined some of the shale samples and aided the writer in many ways. Messrs. Ogden Tweto and John C. Maher of the U. S. Geological Survey aided the writer with information and suggestions. Thanks are due also to Mr. George Bullock and his staff at Philmont Scout Ranch who provided the writer with every convenience while he was doing field work on the ranch. The Water Board of the city of Trinidad Colorado, kindly allowed the writer to enter the restricted area on the headwaters of the North Fork of the Purgatoire River.

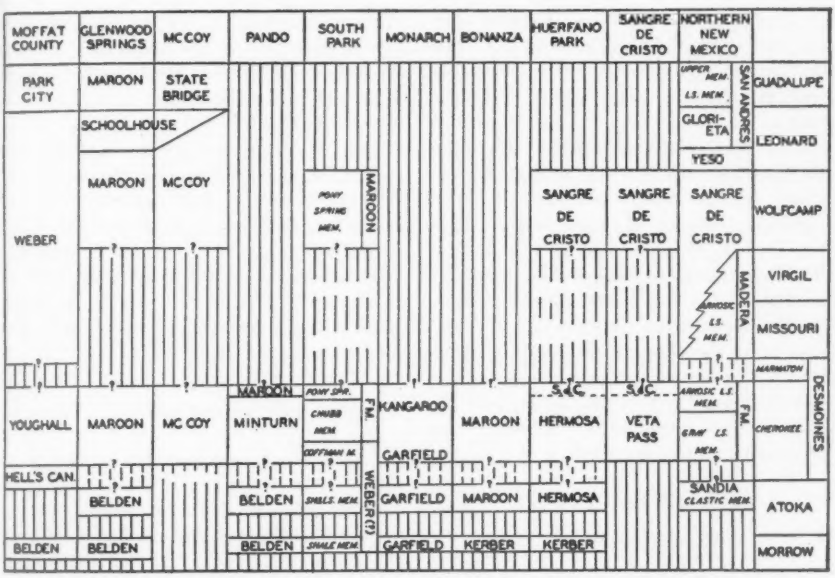


FIGURE 1.— CORRELATION CHART SHOWING THE RELATIVE AGES OF FORMATIONS IN DIFFERENT PARTS OF THE TROUGH

Previous Nomenclature

The stratigraphic nomenclature of the northern part of the trough was summarized by the writer in 1944. Since then the following stratigraphic names have been proposed (Fig. 1): Hell's Canyon and Youghall formations (M. L. Thompson, 1945); "Schoolhouse" sandstone (W. O. Thompson, 1949); Minturn formation (Tweto, 1949); South Canyon dolomite member of the Maroon formation (Bass and Northrop, 1950). Stark *et al.* (1949) made the Coffman conglomerate a member of the Weber (?) rather than the Maroon formation.

No summary of the stratigraphic nomenclature of the southern part of the trough has been made since Girty (1903). Since then the

following stratigraphic names have been applied: Magdalena formation (Gordon, 1907); Yeso formation (Lee, 1909); Veta Pass limestone member of the Sangre de Cristo formation (Melton, 1925b); "Bullington" conglomerate member of the Magdalena formation (Ray and Smith, 1941); and Cortado and Cieneguilla formations (Young, 1946b). The Magdalena group was divided into the Sandia formation (Herrick, 1900) and the Madera formation (Keyes, 1903, p. 339). Read and Andrews (1944) subdivided the Sandia into the lower Limestone member and the upper Clastic member, and the Madera into the lower Gray limestone member and the upper Arkosic limestone member. They also used the term Sangre de Cristo formation in place of Abo formation (Lee, 1909). The San Andres formation (Lee, 1909) has been divided by Read and Andrews (1944) into: the Glorieta sandstone member (Keyes, 1915), the Limestone member, and the Upper member. The terms Hermosa and Rico formations were introduced in Huerfano Park by Burbank and Goddard (1937).

Revised Nomenclature

General Statement

About 45 stratigraphic names have been applied to strata in the trough. Many of these are duplications and are of local significance only. The writer proposes to simplify the nomenclature.

Four widespread lithologic units are recognizable: (1) The Belden-Kerber formations, (2) the Clastic member of the Sandia formation, (3) the Minturn-Madera formations, and (4) the Maroon-Sangre de Cristo formations. In addition there are lithologic units confined to the ends of the trough: (1) the Yeso formation and (2) the San Andres formation at the southern end; (3) the Weber sandstone and (4) the State Bridge formation at the northern end. Although microfossils and megafossils occur in many beds, these strata are more readily divisible into formations on a lithologic basis than on faunal zones.

Mississippian or Pennsylvanian Strata

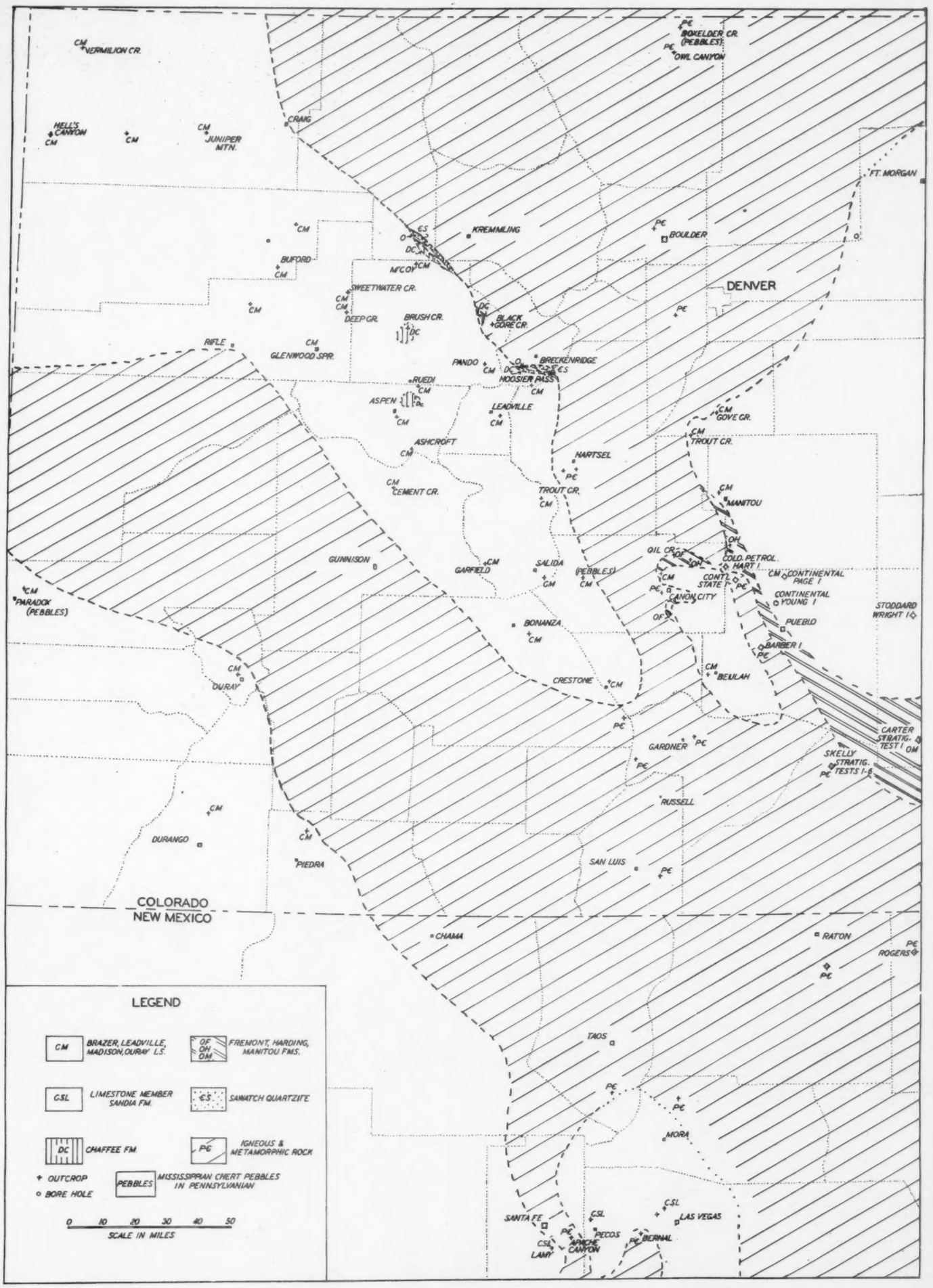
Between the Mississippian and Pennsylvanian strata, a few feet of red, gray, and purple shale occurs locally in the northern end of the trough. Outcrops of this shale may be seen at Reudi (Brill, 1944, p. 653) and along U. S. Highway 6, west of Dotsero. These strata are apparently unfossiliferous remnants of a residual mantle that developed on the Mississippian limestone. This mantle may have formed during either the late Mississippian or the early Pennsylvanian epochs or during both. A part of it may be similar in origin to the Molas formation of southwestern Colorado.

The Limestone member of the Sandia formation, in the southern end of the trough, consists mainly of gray limestone and gray shale and is largely unfossiliferous. The presence of *Endothyra baileyi* in this member in the Sangre de Cristo Mountains (Henbest, 1947) indicates that at least some of this member is Mississippian. The writer has assumed that it is all Mississippian (Pl. 2).

Pennsylvanian Strata

Belden formation.—The beds of dark shale, limestone, and impure coal at the base of the Pennsylvanian section in Colorado were formerly called the Weber shale. For these strata the writer (1942) proposed the name Belden shale member of the Battle Mountain formation. In 1944 he raised the Belden to formational rank. The Belden type of lithology is found in the trough from northwestern Colorado south as far as Huerfano Park (Fig. 2). It to have about the same areal distribution as the Mississippian limestone (*compare* Fig. 2 with Pl. 2) and may have been derived from the erosion of the limestone. An isopach map (Brill, 1944, Fig. 2), while inaccurate in a few details, shows the general distribution and thickness of the formation.

The Belden is partly marine and partly nonmarine. Impure coal has been found at such widely separated localities as Glenwood Springs, Dotsero, Gilman, western South Park, Wellsville, and Bonanza. In Moffat County, the Belden is dominantly marine and contains about 60 per cent limestone. The amount of limestone decreases southward. At Glenwood Springs, Dotsero (Brill, 1944), and on Sweetwater Creek (M. L. Thompson, 1945) the formation contains 50 per cent or less limestone.



PRE-PENNSYLVANIAN PALEOGEOLOGY

Includes data from Darton (1928), Lovering and Johnson (1933), Brainerd, Baldwin, and Keyte (1933), Read and Andrews (1944), Read *et al.* (1944; 1949), Collins (1947), McLaughlin (1947), Maher (1948; 1950).

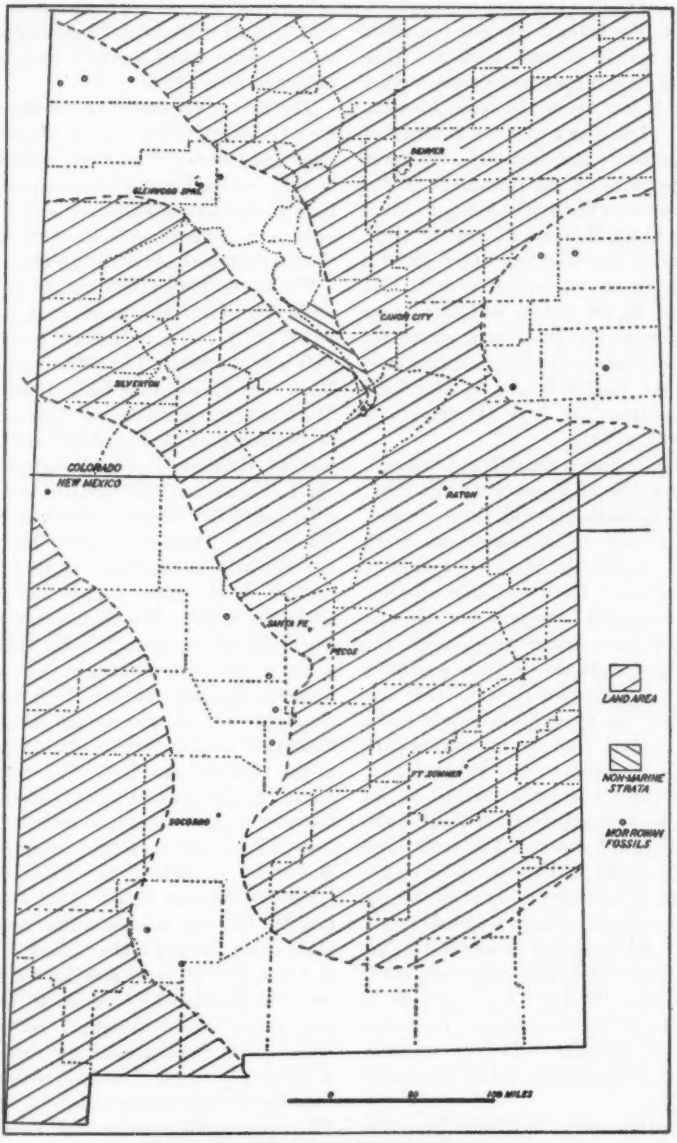


FIGURE 2.— MORROWAN PALEOGEOGRAPHY
Includes data from Thompson (1942), Henbest (1947), Collins (1947), Maher (1948).

Near Reudi (Brill, 1944, p. 653) the lower part of the Belden formation contains little limestone, and the upper part contains less than farther north. The type section of the Belden formation at Gilman (Brill, 1942, p. 1385) is about 125 feet thick and contains about 20 per cent limestone, most of which is in the upper part. Farther south in the vicinity of Leadville

the Belden is 1000–1700 feet thick and contains two members. The lower is 200–300 feet thick and consists mainly of dark shale and thin beds of limestone. Fragments of Pennsylvanian fossils occur 40 feet above the base (Johnson, 1934, p. 37). The upper member consists of limestone, sandstone, and dark shale. The lower member appears to be the equivalent of the Kerber formation at Wellsville (Arkansas River section) and in the Bonanza district. In these areas the Kerber formation consists of 200–300 feet of dark shale and sandstone with thin seams of coal. In the Sangre de Cristo range farther southeast, the basal dark strata are metamorphosed into schist. The southernmost outcrop of the Kerber is east of Grayback Mountain in Huerfano Park (Burbank and Goddard, 1937, p. 941).

The Belden formation has different names in different areas (Fig. 1). In western South Park, the Weber(?) formation (Gould, 1935) is equivalent to the Belden. In this same area, Stark *et al.* (1949) divided the Weber(?) formation into three members: the lower Shale member, the middle Shale and Limestone member, and the upper Coffman conglomerate member. The Coffman conglomerate was originally a member of the Maroon formation (Gould, 1935) but was assigned to the Weber(?) because it had a gradational contact with the underlying dark shale. The writer believes that the two lower members belong in the Belden formation but that the Coffman conglomerate belongs in the overlying Minturn formation. The gradational contact of the Belden with the overlying coarse clastic strata is common everywhere in the trough except in northwestern Colorado. Stark *et al.* (1949, p. 33) state "the name [Weber] has become too firmly established to be discarded". Though the term "Weber" may continue in the vocabulary of the local miners, the writer believes that its scientific value is questionable and it should be abandoned in this area (Brill, 1944, p. 623).

In the Monarch district the Belden formation composes at least part of the Garfield formation (Crawford, 1913). The Garfield formation is metamorphosed, and much of its original color is lost, but it appears to have a basal shale zone similar to the Kerber formation of the Bonanza district and the Shale member of the Belden in South Park. The zone of limestone in the Garfield formation seems to be equivalent to the middle Shale and Limestone member of the Belden in South Park

The Kerber formation of the Bonanza district (Burbank, 1932) and of Huerfano Park (Burbank and Goddard, 1937) consists mainly of dark nonmarine shale and sandstone. The term Kerber formation might well be applied only to the nonmarine facies of the Belden in the southern part of the trough (Fig. 2).

The writer (1944, p. 626) assigned the Belden formation to the Desmoinesian. M. L. Thompson (1945, p. 43) and Henbest (1937) believe that it is Morrowan. The Belden seems to be a facies that crosses time lines. It seems to be Morrowan, it is probably also Atokan, and may be Desmoinesian. A zone of *Millerella* in northwestern Colorado and at Sweetwater Creek (M. L. Thompson, 1945) and Glenwood Springs (Henbest, 1947) indicates that it is Morrowan (Moore and Thompson, 1947). No *Millerella* has been found in the Belden south of Glenwood Springs. In the upper part of the Belden at Glenwood Springs, *Marginifera muricatina* and *Paeckelmannia* sp. occur together. These fossils occur in the midcontinent region where the former is Desmoinesian and the latter Atokan. *Paeckelmannia* sp. occurs high in the Belden formation on Deep Creek north of Dotsero and in the type section (Brill, 1942, p. 1385). In South Park on the east side of Coffman Ridge, *Chonetes* cf. *C. dominus*, *Marginifera ingrata*, and *Spirifer rockymontanus* occur about 300 feet above the base of the middle Shale and Limestone member (Stark *et al.*, 1949, p. 150, bed 3). *Jonesina arcuata* occurs in the black shale about 560 feet higher (Stark *et al.*, 1949, p. 150, bed 5). *Chonetes dominus* was described from the Smithwick of Texas; *M. ingrata* is a local species in the trough; *S. rockymontanus* occurs in the Desmoinesian and Atokan at the southern end of the trough. *J. arcuata* ranges from the Dornick Hills group to the Marmaton. The writer (1950) reported the Belden formation near Whiskey Creek Pass. The basal part of this zone of dark shale and limestone (Intervals 28–38, Whiskey Creek Pass section) may be equivalent to the upper Belden in South Park, but the localities are far apart, and the correlation is questionable. The dark shale at

Whiskey Creek Pass overlies the Clastic member of the Sandia formation and is probably very early Cherokeean.

The Belden formation intertongues with the Minturn formation. The middle Shale and Limestone member of the Belden in South Park is equivalent to the zone of gray limestone that overlies the Kerber formation at Wellsville (Arkansas River section). At this locality the gray limestone is interbedded with red clastic strata and is assigned to the Minturn formation. It contains *Chonetes* cf. *C. dominus* and, among other ostracodes, *Jonesina arcuata*. Henbest (1947) obtained *Millerella* here and so assigned it to the Belden formation. The *Millerella* fauna seems to lie in Interval 46 of the Arkansas River section (Henbest, personal communication) and is about 295 feet stratigraphically above the top of the Belden-Kerber type of lithology. An ostracode fauna in Interval 36 (Arkansas River section), which lies 87 feet below the *Millerella* fauna, is late Atokan or very early Desmoinesian (Mrs. Betty Kellett Nadeau, oral communication). The gray limestone zone may be equivalent to the thin limestone beds that bear *Fusulinella devexa* at Huerfano Park (Pl. 1) and may also be equivalent to beds containing Atokan Fusulinellas in the Crested Butte area (Henbest, 1947).

The ostracode fauna in the Arkansas River section bears little resemblance to that described by McLaughlin (1947) from the Glen Eyrie formation (Fig. 3). If the Glen Eyrie fauna is Atokan as Kellett (1948) suggests, it is earlier Atokan than any in the trough.

The mixture of Atokan and Desmoinesian fossils in the upper Belden and lower Minturn formations suggests that these strata were deposited during a transition period.

Clastic member of the Sandia formation.—The Clastic member can be traced from the southern end of the trough as far north as Huerfano Park. It consists mainly of sandstone and shale with a few thin seams of coal. In the southern end of the trough, this member overlies the Limestone member of the Sandia formation which may be Mississippian; however, where the limestone is absent, the Clastic member rests on Precambrian. Seams of impure coal occur in the Pecos section (Interval 38), in the section east of Mora, and north of Guadalupita. The basal stratigraphic units in both the northern and southern parts of the trough contain coal seams, but there the similarity stops.

The Clastic member is about 300 feet thick in the Pecos, Gallinas River, Coyote Creek, and Whiskey Creek Pass sections, and perhaps as much as 700 feet in western Huerfano Park. No marine fossils have been found in this member between Pecos and Huerfano Park, but the sea presumably was continuous between the two areas

This member has been assigned to the Atokan because of the presence of *Fusulinella famula* (Interval 53, Pecos section), which also is in the Cuchillo Negro formation in the Derryan of central New Mexico (M. L. Thompson, 1948). It lies about 4 feet above a layer containing, among other fossils, *Juresania nebraskensis*, *Marginifera ingrata*, *M. missouriensis*, *Spirifer rockymontanus*, *Composita subtilita*, and *Myalina cuneiformis*. These collections indicate that fossils which are regarded as guides to the Atoka are interbedded with guides to the Desmoines.

In Huerfano Park, Colorado, *Fusulinella devexa* occurs 650 feet above the base of the Clastic member. Dr. M. L. Thompson, who identified the species, states that it also occurs in the Cuchillo Negro formation (Thompson, 1948). The upper part of the member contains several beds of limestone. The member may become more limy north of Huerfano Park and grade laterally into the basal Minturn formation of Wellsville (Arkansas River section) and into the upper Belden formation in South Park. Both of these formations contain a mixed Atokan and Desmoinesian fauna. The presence of *Fusulinella* in the Crested Butte area (Henbest, 1947) indicates that the Atokan sea penetrated as far north as central Colorado.

Several species of *Fusulinella* occur in the Hell's Canyon formation of northwestern Colorado. M. L. Thompson (1945) believes that these are specialized species and has assigned them to the Desmoinesian. This fauna is not known in the trough south of Moffat County. Figure 1 shows a time break throughout the trough during Hell's Canyon time, but it is questionable whether such a break occurred. Possibly the very early Desmoinesian

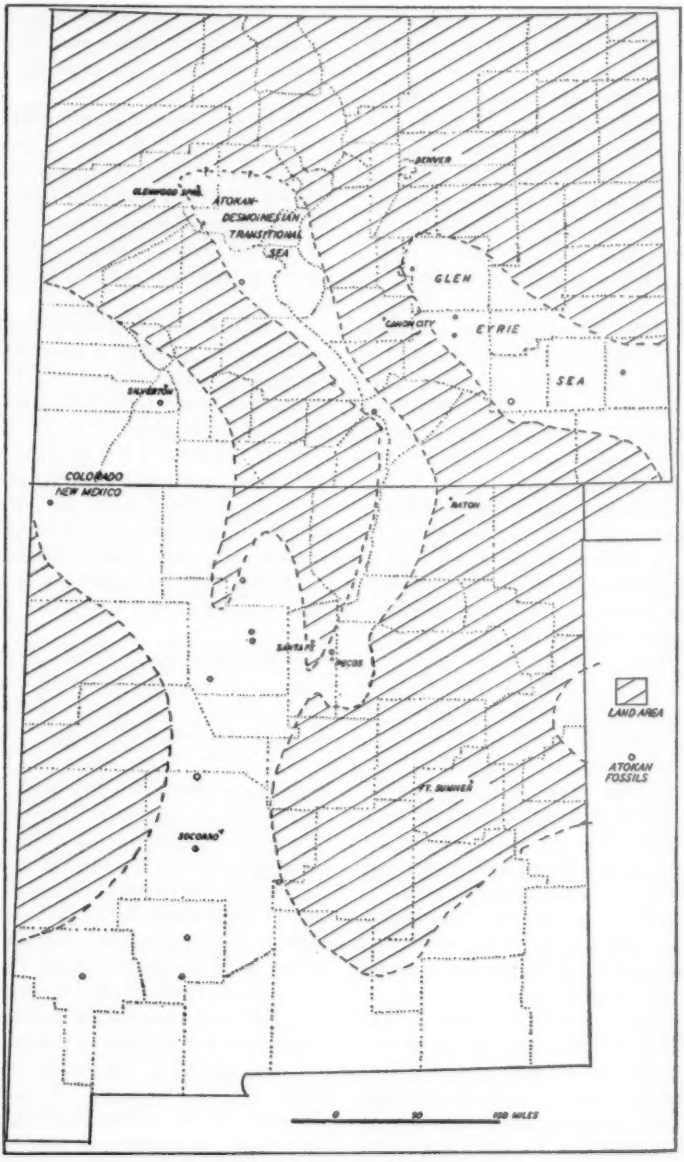


FIGURE 3.— ATOKAN PALEOGEOGRAPHY

Includes data from Thompson (1942; 1948), Henbest (1947), Collins (1947), McLaughlin (1947), Maher (1948).

sea with the *Fusulinella* fauna was entering the northern end of the trough while the Atokan-Desmoinesian transitional sea (Fig. 3) was still present in the southern and central parts of the trough.

Madera and Minturn formations.—Lower

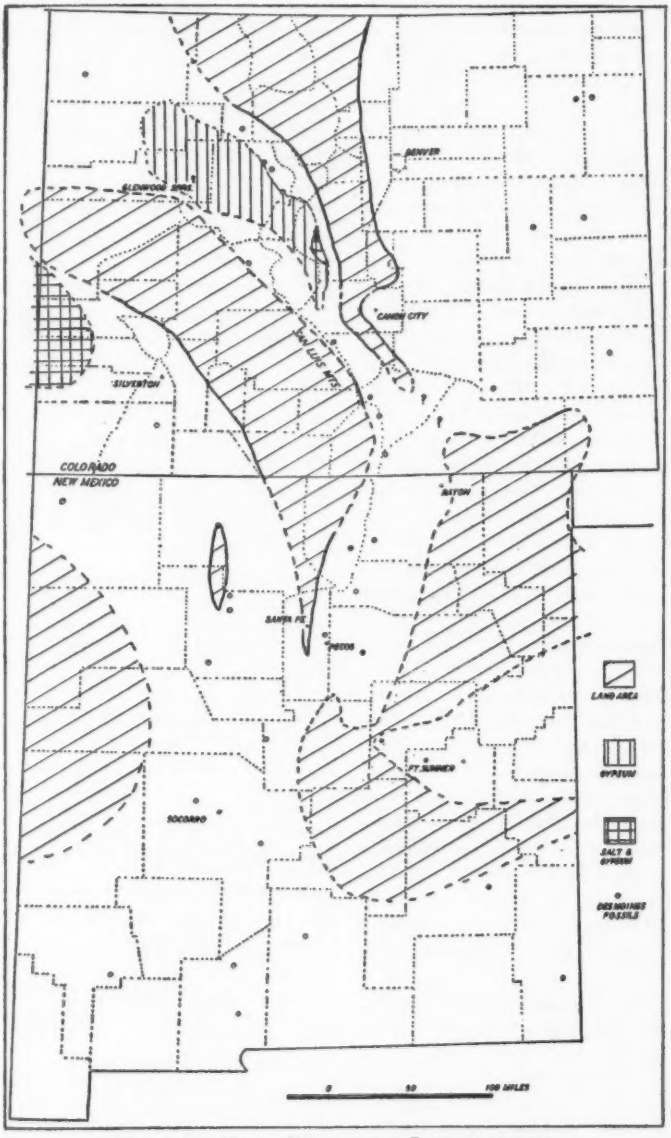


FIGURE 4.— EARLY DESMOINESIAN PALEOGEOGRAPHY
Includes data from Thompson (1942; 1945), Collins (1947), Maher (1948).

Desmoines rocks were deposited throughout the trough (Fig. 4; Pl. 3). They are represented by two formations—the Madera formation in northern New Mexico and Costilla County, Colorado; and the Minturn formation (Tweto, 1949) in the rest of Colorado except for Moffat County.

The Madera formation has been divided into

two members (Read and Andrews, 1944); the lower Gray limestone member and the upper Arkosic limestone member. They are useful in mapping and correlation in the southern part of the trough, although the contact between them is drawn rather arbitrarily (Read and Wood, 1947), as are the contacts between these members and the adjoining formations.

The Gray limestone member is composed of thick beds of gray limestone interbedded with thin layers of clastic rock. It is about 550 feet at Pecos and about 450 feet thick on the Gallinas River. It is poorly exposed on a tributary of Coyote Creek, north of Guadalupita but is probably more than 400 feet thick. At Whiskey Creek Pass, it is more than 500 feet thick. This member is present west of La Veta Pass, Costilla County, Colorado, but the thickness is not known because the section is broken by faults.

The Gray limestone member bears the zone of *Wedekindellina* in the southern part of the trough. Although *Wedekindellina* has not been found in the northern Sangre de Cristo Range, or in the Arkansas River section, or in western South Park, it occurs in the middle of the McCoy and Youghall formations and probably in the middle of the Minturn formation of the Gore area. For this reason, the writer has correlated much of the Minturn and McCoy formations with the Gray limestone member (Pl. 1). An alternate explanation of the distribution of *Wedekindellina* is that this genus entered the trough from both ends but did not reach the area between Pando and Huerfano Park. If this theory is correct, by the time *Wedekindellina* entered the trough more clastic sediment of Cherokeean age had been deposited in the northern part of the trough than in the southern.

The Arkosic limestone member of the Madera formation crops out in the southern part of the trough and is recognizable as far north as Costilla County, Colorado. It is chiefly red and gray arkosic sandstone with beds of shale and conglomerate, with relatively thin beds of sandy, feldspathic limestone from which the name is derived. It is about 1375 feet thick in the vicinity of Pecos, about 2800 feet on Coyote Creek near Guadalupita, and about 2200 feet thick near Whiskey Creek Pass. West of La Veta Pass, its thickness was not measured but may be about equal to that at Whiskey Creek Pass.

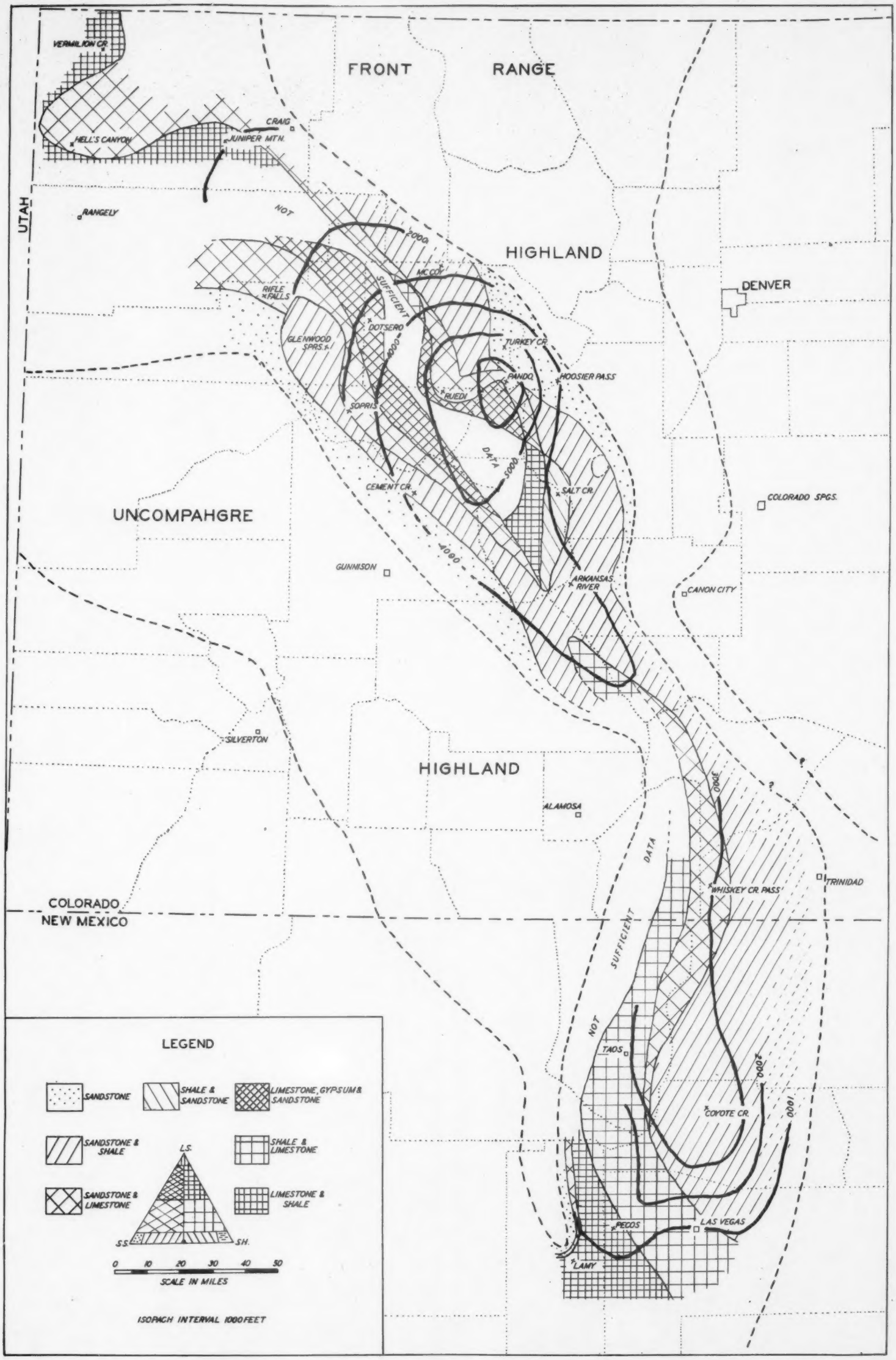
A zone of limestone forms a useful marker in the Arkosic limestone member. It is typically developed in southern Colorado but can be traced into New Mexico. In the vicinity of Whiskey Creek Pass, it is about 150 feet of interbedded sandstone and light-gray sandy oölitic limestone with pelecypods, bellerophontid gastropods, *Domatoceras* sp. and *Ephippioceras* sp. and near the base of the zone *Fusulina novamexicana*. This same bed without fusulinids or cephalopods, on Sangre de Cristo Creek west of La Veta Pass, was called the "Gastropod bed" by Patton *et al.* (1910). What appears to be the same zone of limestone, but without oölites and with a different fauna, occurs along New Mexico Highway 38 at the site of a sawmill at the south end of Moreno Valley about 3 miles north of Black Lake. A bed of gray sandy limestone contains:

Lophophyllidium sp. 5% of fauna
Derbyia crassa Meek & Hayden 9%
Echinoconchus semipunctatus (Shepard) 5%
Linoproductus prattenianus (Norwood & Pratten) 22%
Spirifer rockymontanus Marcou 18%
S. occidentalis Girty 22%
Composita elongata Dunbar & Condra 9%
Composita sp. 5%
Ameura major (Shumard) 5%

In a bed of silty shale about 200 feet higher in the section the following collection was made:

Cup corals 1% of fauna
Mesolobus mesolobus Dunbar & Condra 37%
Marginifera cf. *M. muricatina* Dunbar & Condra 24%
Linoproductus prattenianus (Norwood & Pratten) 24%
Neospirifer cf. *N. triplicatus* (Hall) 7%
Crurithyris planoconvexa (Shumard) 1%
Composita subtilita (Hall) 1%
Euphemites blaneyanus (McChesney) 2%
Glabrocyngulum grayvillense (Norwood & Pratten) 1%
Streblochondria cf. *S. hertzeri* (Miller) 1%
Ephippioceras cf. *E. feratum* (Cox) 1%

This limestone zone crops out on Coyote Creek southeast of Guadalupita and is present on the Mora River, where it is rich in *Composita*. In a



LITHOFACIES AND ISOPACH MAP OF PENNSYLVANIAN STRATA BETWEEN THE JACQUE MOUNTAIN-WHISKEY CREEK PASS LIMESTONES AND THE BASE OF THE SECTION

Method after Krumbein (1948).

gray limestone at the latter locality, the following fossils occur:

Tabulate corals 3% of fauna
Prismopora sp. 2%
Other bryozoa 10%
Derbyia crassa Meek & Hayden 10%
Echinoconchus semipunctatus (Shepard) 2%
Neospirifer cf. *N. triplicatus gibbosus* Dunbar & Condra 3%
Spirifer rockymontanus Marcou 13%
Composita elongata Dunbar & Condra 16%
C. subtilita (Hall) 39%
Crurithyris planoconvexa (Shumard) 2%

This limestone zone occurs in the Pecos section where it is probably Interval 203. Because this zone is a persistent horizon marker in the southern part of the trough, the writer proposes that it be known as the Whiskey Creek Pass limestone member of the Madera formation. It is typically developed at an elevation of about 13,000 feet above sea level on the north side of the north fork of Whiskey Creek, Las Animas County, Colorado.

In this area the bed is strikingly similar in lithology and megafauna to the Jacque Mountain limestone member of the Minturn formation (Brill, 1942, p. 1388). In spite of the fact that the closest exposure of the Jacque Mountain limestone lies 120 miles north of Whiskey Creek Pass, a correlation is suggested because: (1) the molluscan fauna of the two beds is nearly identical; (2) both are oölitic and light gray, and the Jacque Mountain limestone is sandy in its southernmost exposure on Hoosier Ridge (Beaver-Taryall district); (3) both beds occur relatively high in the Pennsylvanian section; (4) the Whiskey Creek Pass limestone is Desmoinesian, and the Jacque Mountain limestone may be the same age although it contains no diagnostic fossils. It may be argued that this lithological and faunal type represents a facies that could occur anywhere in the upper part of the section. There are no oölitic limestone beds in the Pennsylvanian system in the trough as distinctive as these, nor with the same fauna. In the stratigraphic columns (Pl. 1), these two limestone beds and their probable equivalents have been chosen as a datum plane. The correlation of this zone from La Veta Pass to Hoosier Pass must be regarded as tentative; the reasons for it are given in discussing individual areas.

In the vicinity of Pecos, New Mexico, the lower part of the Arkosic limestone member of the Madera formation contains *Fusulina novamexicana* and *F. socorroensis*. *Triticites* cf. *T. nebraskensis* occurs in the upper part of the member and *Triticites rhodesi* occurs at the top of the member. The Fusulinas are indicative of the Cherokeean; *Triticites nebraskensis*, a cylindrical type, is characteristic of the Missourian; *Triticites rhodesi*, a ventricose type, is characteristic of the Virgilian. The zones of *Triticites* have not been found north of the vicinity of Pecos. It is not known whether the upper Pennsylvanian strata grade laterally into nonmarine sediments or whether they are truncated by a pre-Wolfcampian unconformity. It is assumed that they are truncated (Pl. 1), but no clear evidence of an unconformity has been seen.

The Minturn formation in the middle of the trough is the equivalent of the Madera formation. It is recognizable on the eastern side of the trough from the Sangre de Cristo Range as far north as McCoy and consists of the strata between the top of the Jacque Mountain limestone or its equivalent, and the top of the Belden formation or Kerber formation.

The term Minturn formation has been chosen because the type section of the formation is well exposed and contains marine fossils. No essential parts of the section are missing, and there are no misconceptions regarding its name. The use of Minturn for these strata eliminates numerous local names. Most of the formational names previously in use were either ambiguous or applied to relatively unfossiliferous sections. The following formations are more or less equivalent to the Minturn formation, and their names are valid, but they have been rejected in this paper. The Veta Pass member of the Sangre de Cristo formation (Melton, 1925b) is strongly faulted, the base is faulted against the Precambrian, and the position of the top is uncertain. The term Hermosa formation has been applied to these strata (Burbank and Goddard, 1937; Vanderwilt, 1937). The use of this term seems inadvisable because the type section of the Hermosa formation lies in southwestern Colorado in a remote basin of

sedimentation, and the microfauna of the typical Hermosa formation (Roth, 1934) indicates that it is Cherokeean and Marmatonian in age. There is no evidence of marine Marmaton in the trough. The Kangaroo and upper Garfield formations (Crawford, 1913) of the Monarch district are metamorphosed and virtually unfossiliferous. The Maroon formation (Emmons, Cross, and Eldridge, 1894) in the type area is in part Pennsylvanian; however, more recent workers have applied the term to the higher mainly unfossiliferous red beds. The term McCoy formation (Roth, 1930) applies to strata in an isolated area, and the relation of the base to the Belden formation is not known.

The Hell's Canyon and Youghall formations (M. L. Thompson, 1945) are based chiefly on microfaunal zones and are not lithologically typical of most of the trough.

The Minturn formation along the eastern margin of the trough consists chiefly of coarse-grained, red and gray sandstone, interbedded with red and gray shale, and relatively thin beds of carbonate rock. In the Gore area, at least, the basal sandstone beds are not feldspathic, but the overlying clastic layers are arkosic. Thick cyclothems are common in the McCoy, Gore, and Arkansas River areas. Gypsum and perhaps some salt occurs in this formation.

The McCoy formation up to the top of the Jacque Mountain limestone (Interval 93, Donner, 1949) is equivalent to most of the Minturn formation and is about 2927 feet thick. In the Gore area the Minturn formation is 5200 feet thick on Turkey Creek (Brill, 1942, p. 1379) and about 5900 feet thick farther south at Pando (Tweto, 1949). Twelve miles farther east on Hoosier Ridge, it is more than 4200 feet thick, although Singewald (1942) believes that it is somewhat thicker in this area. In western South Park, the Minturn formation consists of the Coffman conglomerate member, the Chubb siltstone member, and the lower part of the Pony Spring siltstone member. It ranges between 2500 and 3500 feet thick. In the Arkansas River section, it is nearly 4200 feet thick.

The Minturn bears *Fusulina distenta* and *F. rockymontana* and probably *Wedekindellina* also. *Wedekindellina* has not been found in the southern area of outcrop. The formation is probably Cherokeean in age except for the basal portion which may be late Atokan in some localities. The contact between the Minturn and the Belden formations is gradational, which suggests continuous deposition in this part of the trough during late Atokan and early Desmoinesian time.

During late Paleozoic time, an intermittent ecological barrier may have existed in southern Colorado. Several lines of evidence suggest that it lay in Huerfano and Custer counties: (1) The Belden-Kerber lithologic type is not known south of Huerfano Park. (2) The Clastic member of the Sandia formation is not known north of Huerfano Park. (3) *Wedekindellina*, associated with the Gray limestone member of the Madera formation, occurs in most sections as far north as Huerfano Park but seems to be absent for nearly 100 miles north of this locality. (4) The species of *Fusulina* are different north and south of this area. *Fusulina distenta* and *F. rockymontana* occur in the Minturn formation as far south as Westcliff, Custer County. On the other hand *Fusulina novamexicana* and *F. socorroensis* occur in the southern end of the trough and are not known north of Huerfano Park. (5) The uplift of the ancient San Luis Mountains (Melton, 1925a) caused a constriction in the trough in this area during Desmoinesian and Wolfcampian (?) time. The barrier was long-lived because the Mississippian limestone wedges out toward the south in Custer County (Pl. 2) and the Entrada sandstone of Jurassic age wedges out toward the south in this same area (C. N. Holmes, oral communication).

Evaporite in the Minturn formation.—Gypsum was deposited near the middle and western side of the trough covering an area of about 5000 square miles. It crops out sporadically from the vicinity of Meeker, Colorado, southward to Coaldale. Salt occurs locally in western South Park. Gypsum has been observed in beds more than 100 feet thick, but most of it has been compressed into domes and irregular structures. Gypsum is associated with fossiliferous limestone north of the town of Minturn (Pl. 1). This bed may be the Robinson limestone member of the Minturn formation. Most of the evaporite in the trough may lie at about the same stratigraphic position. In the Arkansas River section, a bed of gypsum which the

writer calls the Swissvale gypsum member of the Minturn formation lies about 2000 feet above the base of the formation. This is probably the same evaporite that occurs in the Chubb member of the Minturn formation in South Park.

Several theories might be advanced to explain the conditions under which the gypsum formed. A line of calcareous reefs may have formed from 5 to 10 miles off the east shore of the trough and helped to trap the bulk of the coarse clastic sediment between the reef and the eastern shore. This area might then have become heavily loaded with clastic sediment and become depressed, while the area west of the reef remained more or less stable. East of the reef deltaic deposits alternate with relatively thin fossiliferous marine limestone and shale suggesting a cyclical growth of deltas followed by periods of marine invasion. Simultaneously evaporites were being deposited on the stable shelf west of the reefs. The evidence for reefs such as those in postulated is rare in central Colorado. One dolomite reef several hundred feet thick and 1000 feet wide crops out in the valley of Two Elk Creek (Minturn quadrangle, U. S. Geol. Survey) about a mile east of its mouth. It is either the Wearyman, Hornsilver, or Resolution dolomite all of which may be reef deposits (Tweto, 1949). Most of the Pennsylvanian strata west of this reef is eroded from the Sawatch uplift so its relation to the gypsum is not known. Possibly the reefs are stratigraphically lower than most of the gypsum.

A second theory is based on the presence of offshore bars instead of calcareous reefs. It postulates that bars developed along the seaward edge of a central basin platform and enclosed a wide shallow lagoon in which evaporite was precipitated. Normal marine strata were interbedded with deltaic deposits in the area between the bar and the eastern shore of the trough. Young (1946a) postulated the presence of offshore bars in Pennsylvanian strata near Taos, New Mexico, but these were not associated with gypsum. Much cross-bedded sandstone occurs in the Minturn formation, but it is not known that these were deposits formed by bars.

According to a third theory temporary saline lakes formed between the deltas. The fact that fossiliferous marine layers lie immediately above and below the gypsum in many localities throws some doubt on this theory.

The evaporite in the trough may be about the same age as, and genetically related to that in the Paradox Valley and adjacent areas in western Colorado and Utah (Fig. 4).

Permian Strata

Sangre de Cristo formation.—The Sangre de Cristo formation as defined by Hills (1899) comprised the entire Permo-Pennsylvanian section. Melton (1925b) named the lower fossiliferous portion the Veta Pass limestone member and called the coarse conglomerate in the upper part of the formation the Crestone conglomerate phase.

The Arkosic limestone member of the Madera formation grades laterally and vertically into the Sangre de Cristo formation at the southern end of the trough (Read and Wood, 1947). Here the red beds in the two formations are similar, but the limestone in the arkosic member is feldspathic, whereas that in the Sangre de Cristo formation is thin, nodular, and not feldspathic. In southern Colorado, the contact between the Madera formation and the Sangre de Cristo formation is obscure. In this region, the writer proposes that the term Sangre de Cristo formation be redefined to include the Permo-Pennsylvanian strata that overlie the Whiskey Creek Pass limestone or its equivalent.

The Sangre de Cristo formation crops out from the vicinity of Pecos as far north as the Arkansas River valley in Colorado. It is more than 500 feet thick near Pecos, about 2400 feet thick east of Mora, about 9500 feet thick east of Whiskey Creek Pass. It is estimated at more than 5500 feet thick in the Sangre de Cristo Range east of Crestone and is about 8800 feet thick in the valley of the Arkansas River. Piedmont cyclothems characterize the formation. Each cyclothem consists of arkosic conglomerate grading upward into finer-grained clastic strata, and, in some, nodular limestone is present at the top. A great thickness of coarse conglomerate is present in the Crestone conglomerate phase, which crops out in the center of the Sangre de Cristo Range. In this area, boulders of igneous and metamorphic rocks larger than 6 feet in diameter occur in a sand-

stone matrix. The size of the boulders and the thickness of the conglomerate beds diminish both north and south of Crestone. This distribution of coarse fragments led Melton (1925a) to postulate the presence of a local uplift in the vicinity of the present San Luis Park, named the San Luis Mountains.

The exact age of the Sangre de Cristo formation is not clear in all localities. In the vicinity of Pecos, it overlies strata of Virgilian age and underlies Leonardian, and is probably coeval with the Abo sandstone of central New Mexico (Read and Wood, 1947). In southern Colorado it overlies Desmoinesian strata and underlies Jurassic. Either the lower part of the Sangre de Cristo formation in southern Colorado is a nonmarine equivalent of the upper Pennsylvanian marine strata in northern New Mexico, or the Sangre de Cristo is mainly Wolfcamp and the upper Pennsylvanian has been truncated by a pre-Wolfcampian unconformity. If the latter were true the upper Pennsylvanian would wedge out in northern New Mexico, allowing the Wolfcamp to rest on the Desmoines in Colorado. The writer has assumed that this explanation is correct (Pl. 1).

Bones of cotylosaurs and pelycosaurs, found about 1570 feet above the base of the Sangre de Cristo formation in the Arkansas River section (Interval 300) near Howard, occur also in Wolfcamp strata in Kansas, Oklahoma, Texas and New Mexico, and therefore are assumed to occur in the lower Permian strata in Colorado. It is assumed that the Sangre de Cristo formation is mainly Wolfcampian, although it may be late Pennsylvanian.

Maroon formation.—The Maroon formation crops out in the northern part of the trough and is equivalent to the Sangre de Cristo formation. The division between these two formations is placed arbitrarily at the Fremont-Park County line. The name Maroon was proposed for Permo-Pennsylvanian red beds in the Crested Butte area (Emmons, Cross, and Eldridge, 1894). It was used in the Gore area (Tweto, 1949) for strata which overlie the Jacque Mountain limestone. In this paper the Maroon formation includes those strata which overlie the Jacque Mountain limestone or its equivalent and underlie the Weber sandstone or strata younger than Weber. The Maroon formation consists chiefly of red beds which show the piedmont type of cyclothems. On the margins of the trough, the strata are coarse-grained and conglomeratic and contain a few beds of nodular limestone. In the middle of the trough, the strata consist of red siltstone, shale, and fine-grained sandstone, and where the Jacque Mountain limestone is absent or greatly altered in appearance it is difficult to distinguish between the Maroon and Minturn formations. The writer (1944) formerly believed that much of the red siltstone in the middle of the trough was equivalent to the State Bridge formation. Probably much of the upper siltstone and sandstone in the Frying Pan Creek and Woody Creek sections (Brill, 1944, p. 629) is equivalent to the Maroon of the Gore and Crested Butte areas.

The Maroon formation like the Sangre de Cristo formation is either Wolfcampian or late Pennsylvanian. A small fauna occurs in western South Park about 1800 feet above the base of the Maroon formation as defined in this paper (Interval 4 of Gould, 1935, p. 990). The pelecypods resemble *Carbonicola* of late Paleozoic age (N. D. Newell, written communication), and the ostracodes are close to if not identical with *Carbonita tumida magna* which occur in the Missouri, Virgil and Wolfcamp (Kellett, 1935, p. 161). The flora of the Maroon formation has been considered indicative of the Permian (Stark *et al.*, 1949); however, as pointed out in the discussion of the Arkansas River and western South Park areas, many of these plants also occur in Pennsylvanian beds.

Yeso formation.—The Yeso formation (Lee, 1909) consists mainly of red siltstone and fine-grained sandstone. Locally gypsum is interbedded with clastic rock in the upper part of the formation. The formation occurs only in the southern part of the trough and ranges from 600 feet thick on Glorieta Mesa near Pecos (Read *et al.*, 1944) to a knife edge in the vicinity of Ocate, 55 miles to the northwest. Details of this wedge-out are discussed later.

Poorly preserved specimens of *Allorisma* sp., up to 5 mm. in length, are in a limestone bed (Interval 370, Pecos section) in the upper Yeso west of Rowe, New Mexico. These dwarfed pelecypods probably represent the northernmost extension of the Yeso sea. The Yeso is

considered Leonardian (Needham and Bates, 1943).

Glorieta sandstone.—The San Andres formation has been divided into three members (Read and Andrews, 1944): The Glorieta sandstone member at the base, the Limestone member in the middle, and the Upper member at the top. The Glorieta sandstone, a persistent bed of medium-grained, white, clean quartz sandstone, crops out in the southern part of the trough as far north as Ocate. It ranges between 100 and 300 feet thick (Fig. 5). The sandstone is unfossiliferous, but from its stratigraphic position it has been assigned to the Leonardian (Needham and Bates, 1943, p. 1664). The Glorieta sandstone is correlated with the Lyons sandstone of eastern Colorado on the basis of lithology and stratigraphy (Oborne, 1941).

The two upper members of the San Andres formation may be Guadalupian.

Weber sandstone.—The Weber sandstone (King, 1876) occurs in the vicinity of the Uinta Mountains, Utah. It consists of white or yellow, clean quartz sandstone, or in some localities quartzite, and ranges up to 1400 feet thick in northeastern Utah and northwestern Colorado (Fig. 5). At the outcrop in Moffat County, Colorado, the formation is 800–900 feet thick (Brill, 1944). It is about 60 feet thick near a small district school on the east fork of Flag Creek, Rio Blanco County (Brill, 1944, p. 633). It is probably this exposure that led W. O. Thompson (1949, p. 72) to name this bed the "Schoolhouse" sandstone. This bed is clearly a tongue of the Weber sandstone, and the writer proposes that Thompson's term be applied to it. The Schoolhouse tongue of the Weber sandstone is 79 feet thick at South Canyon near Glenwood Springs. (The writer in 1944 erroneously reported the thickness as 100 feet.) It is 46 feet thick 4 miles north of Eagle (Brill, 1944, p. 649, Interval 77), has the same thickness and stratigraphic position near Sylvan station, 10 miles north of Eagle and is 27 feet thick 10 miles east of Eagle (Brill, 1944, p. 650, Interval 72). On the west side of the McCoy area (Murray, 1949), it is 59 feet thick and lies between the McCoy formation and the State Bridge formation. W. O. Thompson (1949) traced this tongue over the same area.

The age of the Weber sandstone is in question. In eastern Utah, its basal contact is gradational with the Morgan formation which is Desmoinesian, and the top is overlain unconformably by the Park City formation which is Guadalupian (Williams, 1943). In Moffat County, Colorado, the Weber has been assigned to the late Pennsylvanian (Moore and Thompson, 1947). The Schoolhouse tongue of the Weber may be equivalent to the Lyons sandstone (W. O. Thompson, 1949), and therefore Leonardian in age. The Weber could conceivably be a transgressive sandstone belonging to several or all of the following epochs: Desmoinesian, Missourian, Virgilian, Wolfcampian, and Leonardian. The isopach map of the Weber, Lyons, and Glorieta sandstones (Fig. 5) shows the total thickness of the Weber sandstone in the vicinity of the Ancestral Rockies, but does not imply that the entire Weber is Leonardian. If any of the Weber is Leonardian it is probably the upper few feet.

State Bridge formation.—The type section of the State Bridge formation is in the McCoy area (Brill, 1942, p. 1392). On the eastern side of the McCoy area it overlies the Maroon formation, but on the western side the Schoolhouse tongue of the Weber sandstone lies between the Maroon and State Bridge formations (Murray, 1949). In the type area the formation is 525 feet thick and consists of dark red and yellow siltstone and shale. About 140 feet above the base a calcareous sandstone bears a pelecypod fauna. Ten miles west of Eagle the formation is 344 feet thick, rests on the Schoolhouse tongue, and the same pelecypod fauna occurs 90 feet above the base (Brill, 1944, p. 650, Interval 73 and 74). About 4 miles north of Eagle on Eiby Creek, the State Bridge formation is about 760 feet thick (Brill, 1944, p. 648).

In the vicinity of Glenwood Springs, a bed of dolomite about 6 feet thick occurs in the upper red beds. This bed has been named the South Canyon dolomite member of the Maroon formation (Bass and Northrop, 1950). Its fauna, which is molluscan, seems to resemble that of the Phosphoria formation. This dolomite bed appears to be the Interval 70 assigned to the Triassic (Brill, 1944, p. 643). It lies between layers of red shale and siltstone, about 100 feet above the top of the Schoolhouse tongue and about 100 feet below the "Shinarump conglom-

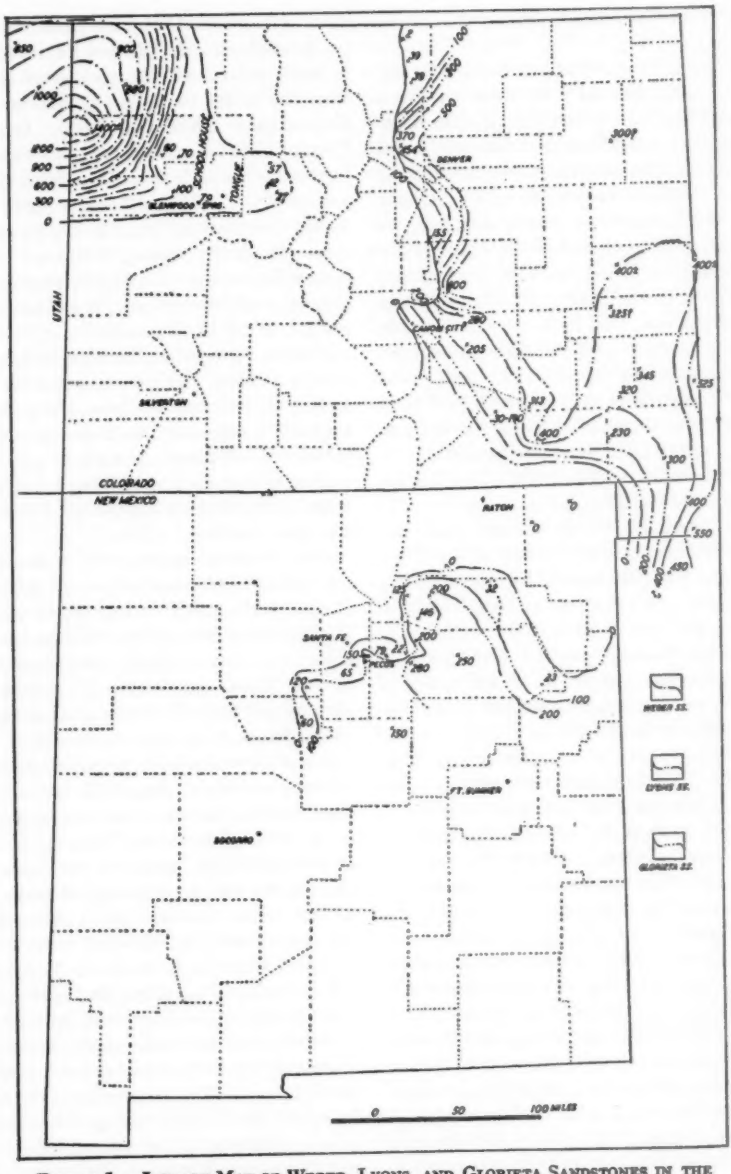


FIGURE 5.— ISOPACH MAP OF WEBER, LYONS, AND GLORIETA SANDSTONES IN THE VICINITY OF THE ANCESTRAL ROCKY MOUNTAINS

erate", in the same stratigraphic position as the State Bridge formation. The writer has by definition limited the Maroon formatio to beds that underlie the Schoolhouse tongue of the Weber sandstone; therefore the South Canyon dolomite seems to be a member of the

State Bridge formation. It is probably equivalent to the pelecypod-bearing bed in the type section of the State Bridge formation.

The red siltstone and sandstone beds on Gypsum, Frying Pan, and Woody creeks, assigned to the State Bridge formation by the writer (1944, p. 636), are probably older than the State Bridge and are equivalent to the Maroon formation.

If the correlation of the South Canyon dolomite with the fossiliferous limy bed in the type section of the State Bridge formation is correct, the formation is Guadalupian.

Structural Considerations

The amount of uplift in the Front Range and Uncompahgre highlands can be computed if certain assumptions are made. In the portion of the trough between Glenwood Springs and Salida, Colorado, the area of sedimentation is a little more than 11,000 square miles. If the average thickness of the strata between the base of the Belden and the top of the Maroon formation is 1.5 miles (7950 feet), the volume of sedimentary rock in this area is about 16,650 cubic miles. Igneous rock when weathered increases its volume by 51 per cent (Leith and Mead, 1915, p. 19), making 11,100 cubic miles the volume of the original unweathered igneous rock. However it may be erroneous to assume an increase of 51 per cent, because most of the weathering was mechanical rather than chemical.

The area of the Uncompahgre highland between Glenwood Springs and Salida is about 12,000 square miles. If the divide between the watersheds to the east and west lay in the middle of the highland, about 6000 square miles would have furnished sediment to the zeugogeosyncline. Under the same conditions, about 2000 square miles of the Front Range highland would also have furnished sediment. If 11,100 cubic miles of fresh rock were removed from this 8000 square miles of land area, the average amount of uplift must have been about 1.4 miles. It is not assumed that the highlands stood 1.4 miles above sea level at any time. Very likely they were eroded nearly as rapidly as they rose.

The downwarping and filling of the trough was probably relatively rapid during and after Desmoinesian time. At Red Canyon east of Gardiner, Colorado, the red beds of the Sangre de Cristo formation thicken westward at the rate of about 135 feet vertically to 375 feet horizontally, equivalent to about 1900 feet per mile. In the Kokomo district, Summit County, the Minturn formation thickens westward by about 600 feet per mile (Tweto, 1949, p. 157).

The rapid downwarping of a relatively narrow basin such as this zeugogeosyncline must have been accompanied by faulting on at least one side. On the boundary of a rising landmass and subsiding trough the faults should form subparallel to the margin of the trough and be downthrown on the basinward side. Faults such as the Gore, Mosquito, London, and Coaldale lie subparallel to the eastern side of the trough and are down thrown on the basinward side. They were undoubtedly set in motion during the Laramide Revolution but may have been active in Permo-Pennsylvanian time. The western side of the trough in Colorado has no visible faults comparable to these, but as the western margin is covered with strata younger than Permian, any such faults would be covered. On the other hand, the Uncompahgre highland may have been a ramp uplift with a gentle slope on the eastern side and a steep fault scarp on the western margin. The large faults subparallel to the western side of the Uncompahgre highland give some credence to this theory.

The lower part of the Pennsylvanian section contains more carbonate rock on the western side of the trough than on the east side. This distribution indicated to Vanderwilt (1935, p. 1677) that all lower Pennsylvanian strata were derived from the Front Range highland. According to the theory of ramp uplift the eastern slope of the Uncompahgre highland would have been gentle during the early stages of uplift. This might account for the presence of fine-grained sediment close to the western shore of the trough.

The Maroon formation is fine-grained near the middle of the trough and coarser-grained on the sides, which indicates derivation from both highlands.

The lithofacies map of the trough (Pl. 3) was prepared as suggested by Krumbein (1948).

The writer computed the sand-shale ratio and clastic ratio of the sections located on the map. The map shows the lithofacies of strata between the base of the Pennsylvanian and the Jacque Mountain-Whiskey Creek Pass limestones or equivalent bed. As these formations are not recognizable on the western side of the trough, this part of the map is subject to correction.

The Pennsylvanian strata below the Jacque Mountain-Whiskey Creek Pass limestones are Morrowan, Atokan and Cherokeean in age. The Cherokee strata are thickest, therefore the distribution of coarse- and fine-grained sediment of Cherokeean age is the dominant influence on the pattern of the map. During Cherokeean time, at least, sediment was being derived from both sides of the trough. During Morrowan and Atokan time, less sediment may have entered the trough from the west than from the east.

Discussion of Areas

Northern New Mexico

Pennsylvanian.—The southern end of the zeugogeosyncline is constricted between peninsular portions of the southern Uncompahgre and northern Pedernal highlands (Read and Wood, 1947, Fig. 2), but more of the Pennsylvanian formations and faunas were able to pass into the trough from the central New Mexico basin

Between Lamy and Las Vegas, the members of the Sandia and Madera formations are exposed over a wide area (Read and Andrews, 1944; Read *et al.*, 1944); however, individual beds show rapid lateral changes in lithology and thickness. At Lamy, the Clastic member of the Sandia formation and the Gray limestone member of the Madera formation are less than 300 feet thick; 10 miles northwest at Pecos they are about 1000 feet thick. Irregularities in the floor of the trough caused the Pennsylvanian sediments to thicken and thin. The Clastic member of the Sandia formation thins several hundred feet per mile against a former granitic island just west of Tres Hermanos on Bernal Creek (Bernal quadrangle, U. S. Geol. Survey). The sedimentary environment of the Pennsylvanian was that of a geosyncline, but the Gray limestone member of the Madera formation was probably a platform deposit (Sidwell, 1948, p. 101).

Much of the Pennsylvanian strata is marine and richly fossiliferous. Typical faunas are listed as they occur in the Pecos detailed section.

On Gallinas River northwest of Las Vegas, the section is similar to that at Pecos, except that the upper part of the Arkosic limestone member of the Madera formation has been eroded. Numerous fusulinids occur (Needham, 1937). The writer measured a detailed section and collected the following fossils from a gray crystalline limestone in the Gray limestone member of the Madera formation 80 feet above the base of the member:

Fusulina euryteines Thompson
F. novamexicana Needham
Chaetetes milleporaceous Edwards and Haime
Marginifera sp.
Crurithyris planoconvexa (Shumard)
Hustedia mormoni (*Marcou*)
Cryptacantha whitei Dunbar and Condra
Phricodothyris perplexa (McChesney)
Composita sp. small
Cleiothyrodina orbicularis (McChesney)

Another collection comes from a light-gray limy shale about 250 feet above the base of the same member.

Lophophyllidium sp. very large 18% of fauna
Linoproductus sp. 6%
Dictyoclostus portlockianus (Norwood and Pratten) 3%
Marginifera haydenensis (Girty) 31%
Spirifer rockymontanus Marcou 15%
Spirifer cf. *C. occidentalis* Girty 6%
Crurithyris planoconvexa (Shumard) 12%
Composita subtilita (Hall) 3%
Allorisma terminale Meek and Hayden 3%
Euconospira turbiniformis (Meek and Worthen) 3%

The following collection came from a gray sandy limestone in the Arkosic limestone member of the Madera formation about 220 feet above the base of the member:

Fusulina socorroensis Needham 40% of fauna
Bryozoans 6%
Derbyia crassa (Meek and Hayden) 6%

Dictyoclostus portlockianus (Norwood and Pratten) 16%
Linoproductus prattenianus (Norwood and Pratten) 8%
Phricodothyris perplexa (McChesney) 6%
Composita subtilita (Hall) 18%

Pleurodictium eugeneae (White) and *Neospirifer cameratus* (Morton) occur in a gray limestone in the Arkosic limestone member about 610 feet above the base of the member.

On the north side of the Mora River, the Pennsylvanian section is well exposed but broken by faults. A bed of dark-gray shale crops out beside New Mexico Route 3 at a highway sign which reads "Watch out for cattle", about 3.5 miles east of Mora. This bed is in the Arkosic limestone member of the Madera formation and lies about 350 feet stratigraphically above the equivalent of the Whiskey Creek Pass limestone. It contains the following fossils:

Fusulina sp. 2% of fauna
Stromatoporoid 19%
Chonetes granulifer (Owen) 20%
Mesolobus mesolobus (Norwood and Pratten) 2%
Echinoconchus semipunctatus (Shepard) 2%
Linoproductus sp. 2%
Dictyoclostus portlockianus (Norwood and Pratten) 2%
Neospirifer goreii (Mather) 2%
Crurithyris planoconvexa (Shumard) 2%
Astartella concentrica McChesney 2%
Myalina cuneiformis (Gurley) 2%
Nuculana sp. 2%
Aviculopecten cf. *A. flabellum* (Price) 2%
? Orthonychia parva (Swallow) 2%
Trachydomia sp. 4%
Glabrocyngulum grayvillense (Norwood and Pratten) 4%
Pharkidonotus pericarinatus (Conrad) 4%
Soleniscus regularis (Cox) 4%
Pseudozygopleura scitula (Meek and Worthen) 2%
P. cf. *P. williamsi* Knight 4%
Pseudorthoceras sp. 2%
Fish teeth 4%

The highest fossiliferous bed in the section, about 620 feet above the Whiskey Creek Pass limestone, consists of greenish-gray silty shale and contains *Dictyoclostus portlockianus* (Norwood and Pratten) and *Myalina wyomingensis* (Lea).

The section on Coyote Creek near Guadalupita is similar to that on the Mora River. It is broken by faults and not so well exposed and not so fossiliferous as the sections farther south.

A portion of the Arkosic limestone member of the Madera formation crops out just south of the divide at the south end of the Moreno Valley. At this locality the limestone zone that is equivalent to the Whiskey Creek Pass limestone crosses New Mexico Route 38 at the site of a sawmill. This zone is separated from the Sangre de Cristo formation by faults. Strata here were assigned to the Cieneguilla formation (Young, 1946b).

The gray limestone member and the lower part of the Arkosic limestone member exposed on the divide north of Fernando de Taos Creek were named the Cortado formation by Young (1944b). He states (1946a) that this formation contains 69 cyclothems that resulted from uplifts of the Uncompahgre highland, and also that some of the sandstone beds in this formation may have been offshore bars migrating shoreward. Young (1942) described some of the molluscan fauna of this formation, and Needham (1937) reported *Fusulina taosensis* and *F. euryteines* in these strata. Fusulinids and megafossils of Desmoinesian age occur along U. S. Highway 64 east of Palo Flechado Pass, and Desmoinesian megafossils occur on the property of the Springer Cattle Company on the east side of Moreno Valley south of Agua Fria.

Permian.—In the zeugogeosyncline, where faunal evidence is lacking, the Virgil-Wolfcamp contact is drawn arbitrarily in the Sangre de Cristo formation. The upper Sangre de Cristo formation in the southern part of the trough is equivalent to the Abo formation, which is Wolfcampian. In the Pecos region, the Sangre de Cristo formation is underlain by Virgil rocks and overlain by the Yeso formation of Leonardian age. The Yeso formation consists mainly of red siltstone and is 300–600 feet thick on Glorieta Mesa. It is overlain by the Glorieta sandstone. The Yeso formation can be traced northeastward into Mora County. It pinches and swells indicating unconformable contact with the Glorieta. On Sapello Creek, 12 miles north of Las Vegas, nearly 300 feet of Yeso lies between a limy, quartz-pebble conglomerate in the upper Sangre de Cristo formation and the Glorieta sandstone. Eight miles farther

north, on Cebolla Creek, about 150 feet of Yeso lies between the conglomerate and the Glorieta sandstone. On Mora River, 4 miles farther north, about 190 feet of Yeso lies between these two layers. Near the town of Coyote, 11 miles farther north, the Glorieta sandstone rests on the conglomerate, and the Yeso formation is absent. East of Guadalupita, about 8 miles north of Coyote, about 75 feet of Yeso separates the conglomerate and the Glorieta sandstone. Near Ocate, about 7 miles northeast of Guadalupita, the Glorieta rests on the conglomerate. On Cimarroncito Creek, Colfax County, the Glorieta and Yeso formations and the limy conglomerate are absent, and a sandstone similar to the Entrada rests on the Sangre de Cristo formation. About 900 feet of the Sangre de Cristo is exposed, but it is intruded by porphyry and locally metamorphosed. Smith and Ray (1943) state that the "Bullington" conglomerate member of the Magdalena formation lies 100 feet below the Dakota-Magdalena contact on Cimarroncito Creek. The present writer believes that the Dakota sandstone is in contact with the Morrison formation at this locality, and that the "Bullington" conglomerate here, as in the type locality (Ray and Smith, 1941), is a coarse-grained facies of the Morrison formation.

The Sangre de Cristo formation contains beds of very coarse conglomerate northwest of Eagle Nest, Colfax County. A few miles west on Larkspur Peak, five beds of puddingstone conglomerate (Gruner, 1920) occur about 1000 feet above the base of the section. Presumably this area was close to the Uncompahgre highland in Permian time.

Whiskey Creek Pass

Description.—The Whiskey Creek Pass section was measured between the Precambrian granite and the Entrada sandstone across the crest of the Culebra Range from the vicinity of Whiskey Creek Pass to Monument Lake. The section is broken by faults and is fragmentary, but it illustrates the lithologic character of the late Paleozoic strata.

Pennsylvanian.—The basal 3000 feet of the section, although faulted, is fairly complete. It is well exposed above timber line in cirques on both sides of the range. The Clastic member of the Sandia formation appears to rest unconformably on the Precambrian. In a gap about three-fourths of a mile north of the west portal of the Whiskey Creek Pass tunnel, the basal 10 feet of the section consists of buff and dark reddish-brown sandstone, overlain by 17 feet of dark reddish-brown sandstone and shale. In the next stream valley, about a mile north of the gap, the basal 6 feet of dark-gray, coarse-grained sandstone is overlain by 15 feet of medium-gray silty shale, overlain by more than 50 feet of red sandstone. This suggests that either the sediments overlap the granite toward the south or the contact is a fault.

Both members of the Madera formation are present here. The presence of dark shale and muddy limestone in the base of the Gray limestone member led the writer (1950) to suggest that this was equivalent to the Belden formation of central Colorado, but, although it contains *Neolobus striatus*, it may be younger than most of the Belden. The upper part of the member contains *Fusulina taosensis* which occurs in the lower Cherokee in New Mexico.

The Arkosic limestone member of the Madera formation overlies the Gray limestone member and is about 2200 feet thick. It consists mainly of gray and green sandstone and shale interbedded with sandy limestone and dolomite. A zone of interbedded sandstone and light-gray, sandy, oölitic limestone in the upper part of the member is about 150 feet thick and contains *Fusulina novamexicana*, pelecypods, bellerophontid gastropods, *Domatoceras* sp., and *Ephippioceras* sp. The writer has proposed the name Whiskey Creek Pass limestone member of the Madera formation for this zone because it seems to have a wide areal distribution in northern New Mexico and southern Colorado. It may correlate with the Jacque Mountain limestone of the Gore area which is similar in lithology and fauna. Its possible correlation with the Rico formation is discussed later.

Permian (?).—The contact of the Pennsylvanian and Permian here, as elsewhere in the trough, is drawn arbitrarily a few hundred feet above the Whiskey Creek Pass limestone. The detailed section of the Sangre de Cristo formation was measured on the North Fork of the Purgatoire River and the West Fork of the

North Fork and on Whiskey Creek. The formation consists largely of nonmarine red beds deposited as piedmont cyclothems. It is more than 9600 feet thick. The upper 3300 feet contains numerous beds of dark reddish-brown siltstone and sandstone. The siltstone resembles the Yeso formation in lithology and weathering. The Yeso formation appears to wedge out in northern New Mexico, but it may interfinger with the Sangre de Cristo formation here.

The total thickness of the Permo-Pennsylvanian in this area is more than 11,650 feet. The same strata between the South and Middle forks of the Purgatoire River are about 13,045 feet thick (Lee and Knowlton, 1917, p. 41–42).

La Veta Pass

Pennsylvanian.—The Pennsylvanian strata are exposed along U. S. Highway 160 west of La Veta Pass, Costilla County, Colorado. The Madera formation is overlain by the Sangre de Cristo formation. The section is faulted and intruded by porphyry. The Gray limestone member of the Madera formation is in contact with Precambrian rocks on the west side of the area. The contact near Russell Post Office has been mapped as an unconformity (Patton *et al.*, 1910), but the writer believes that along Placer Creek this is a fault contact because: (1) strata containing *Wedekindellina* are in contact with the granite, whereas both north and south of this area older strata separate the *Wedekindellina* zone and the granite, and (2) beds of fossiliferous limestone are folded steeply against the granite and are truncated by it. The member seems to contain less limestone here than in the Whiskey Creek Pass or Huerfano Park areas.

The Gray limestone member is overlain by the Arkosic limestone member of the Madera formation, but the contact was not observed or the thickness of each member measured. Patton *et al.* (1910, p. 29–30) state that the "Gastropod bed", B-4, lies 3138 feet above the base of the section. Girty (Patton *et al.*, 1910, p. 30) says "B-4 . . . might possibly be Rico so far as fossils are concerned . . . ; however it might also be Hermosa". Bed B-4, which crops out along the highway about 4.3 miles east of Russell Post Office, is the upper limestone bed of a zone of interbedded limestone and sandstone. The zone is about 160 feet thick; the limestone beds are light gray, oölitic, and sandy, and contain pectinoid pelecypods and gastropods. This is almost certainly the Whiskey Creek Pass limestone.

The term Veta Pass limestone member of the Sangre de Cristo formation was proposed for dark limestone and shale, arkose, and micaceous shale in the lower part of the section (Melton, 1925b). Its type section is along Placer Creek north of Russell Post Office. Melton believed that the member was about 2100 feet thick, but the top of the member cannot be placed exactly. If the top were drawn at the Whiskey Creek Pass limestone, 3138 feet (Patton *et al.*, 1910) would be more nearly correct than 2100 feet.

A zone of *Wedekindellina-Fusulina* has been reported at La Veta Pass (Henbest, 1947). The writer collected *Wedekindellina* sp. from beds of limestone along Placer Creek 1.5 miles north of Russell Post Office and at the mouth of Willow Creek about 3 miles east of Russell Post Office. Megafossils are abundant in some beds (Patton *et al.*, 1910; Johnson, 1929).

Permian (?).—Faults separate the fossiliferous Pennsylvanian strata from the overlying red beds of the Sangre de Cristo formation. The Whiskey Creek Pass limestone is assumed to be the contact between the Arkosic limestone member of the Madera formation and the Sangre de Cristo formation. The Sangre de Cristo formation is faulted, intruded and poorly exposed, but scattered outcrops occur near U.S. Highway 160 both east and west of La Veta Pass. Melton (1925b) states that the red beds are about 6000 feet thick in the Culebra Range but mentions no specific locality. As the red beds seem to be thicker than 6000 feet both north and south of La Veta Pass, their thickness here may be as much as 8000 feet.

Huerfano Park

Pennsylvanian.—Late Paleozoic strata are exposed in numerous fault blocks along the Huerfano River and Greaser Creek in northwestern Huerfano County.

Burbank and Goddard (1937) gave a generalized columnar section for this area, stating that the total thickness is not known because

of faults. Locally the base of the section seems to vary lithologically. The base of the section west of Grayback Mountain in the drainage of Manzaneres Creek consists of carbonaceous shale, sandstone, and thin limestone. These strata are about 300 feet thick and are assigned to the Kerber formation (Burbank and Goddard, 1937). The immediately overlying strata were assigned to the Hermosa formation, which consists of arkosic grit, shale, and limestone of unknown thickness. Marine fossils occur at the base of the Hermosa formation which Girty believed showed "a few rather tenuous relations with the fauna of the Morrow group of Arkansas" (Burbank and Goddard, 1937, p. 942).

The base of the Pennsylvanian section was measured in detail on the north side of the Huerfano River (E½, sec. 23, T. 27 S., R. 72 W. Although the section is partly covered, the strata consist mainly of gray sandstone and conglomerate which rests unconformably on the Precambrian metamorphic rocks. The dark shale of the Kerber formation is missing here. The lowest bed containing marine fossils is a sandy limestone about 653 feet above the base. It contains *Fusulinella devexa*, *Lophophyllidium* sp., *Linoproductus* sp., and *Composita subtilita*. *F. devexa* is found in the upper Atoka (Derryan) of New Mexico (M. L. Thompson, 1948). The lower 700 feet of the section seems to be equivalent to the Clastic member of the Sandia formation. This is the lower part of the Hermosa formation of Burbank and Goddard (1937) and is presumably underlain by the Kerber formation. The writer did not see the contact of the Kerber and Sandia formations.

The overlying Pennsylvanian section is exposed in a series of fault blocks eastward along the river. Probably both the Gray limestone member and the Arkosic limestone member are present here, but the writer could not locate the contact. *Fusulina* sp. and Desmoinesian megafossils occur in several beds.

Portions of the Pennsylvanian section are exposed in fault blocks on a large tributary on the south side of Greaser Creek (Burbank and Goddard, 1937, Pl. 7). One block contains six beds of medium dark-gray oölitic limestone 7 to 30 feet thick, separated by beds of gray sandstone and sandy limestone. Some of the oölitic beds contain *Composita* sp. They differ in lithology and fauna from the typical Whiskey Creek Pass limestone, and although they are Desmoinesian in age, they are probably not its equivalent. A gray calcareous shale in another block in the same area contains:

Lophophyllidium sp. 2% of fauna
Ethelocrinus sp. 1%
Prismopora sp. 2%
Rhombopora sp. 6%
Other bryozoans 8%
Dictyoclostus semireticulatus hermosanus, (Girty) 28%
Spirifer rockymontanus Marcou 3%
Punctospirifer kentuckyensis (Shumard) 6%
Hustedia mormoni (Marcou) 12%
Composita subtilita (Hall) 4%
Myalina cuneiformis ? Gurley 1%
Edmondia gibbosa ? Geinitz 1%
Schizodus cuneata ? Meek 3%
Straparollus sp. 1%

This fauna seems to lie stratigraphically higher than the oölitic limestones and appears to be Desmoinesian.

About 400 feet of red beds overlying the Hermosa formation has been assigned to the Rico formation (Burbank and Goddard, 1937). Girty states that these beds contain marine fossils that "may represent the fauna of the Permian Rico formation". The fauna is not listed by Burbank and Goddard, and the writer did not find it; however, if this fauna should prove to be the same as that referred questionably to the Rico by Girty in the La Veta Pass area (Patton *et al.*, 1910, p. 30), it might be equivalent to the Whiskey Creek Pass limestone. There seems to be confusion regarding the Rico formation in southwestern Colorado except in the type area. For this reason it seems inadvisable to apply this stratigraphic name to strata east of the Uncompahgre highland.

Permian (?).—The Permo-Pennsylvanian contact is obscure in this area. The red beds of the lower parts of the Sangre de Cristo formation are well exposed on Greaser Creek and the Huerfano River where they consist mainly of arkosic sandstone and conglomerate with pebbles up to 3 inches in diameter. Burbank and Goddard (1937) suggest that they are about 4000 feet thick. They are overlain by the Crestone conglomerate phase of the Sangre de Cristo formation.

North of Medano Pass, the Crestone con-

glomerate phase rests on the Precambrian granite. According to Melton (1925b), the overlapping of the conglomerate on the granite and the wedging out to the west of the lower Sangre de Cristo formation indicate that this area approximates the former western margin of the trough.

Red Canyon

Red Canyon is on the western slope of the Wet Mountains about 7 miles airline east of Gardiner, Huerfano County. The upper red beds lie between the Precambrian metamorphic rocks and the Entrada sandstone. The red strata are divisible into two units. The lower, 56–176 feet of coarse-grained arkose and boulder-conglomerate, correlated with the Sangre de Cristo formation (Hills, 1900), is overlain by 27–50 feet of fine-grained red sandstone, named the Badito formation (Hills, 1900). The contact between the two units is distinct. The Sangre de Cristo formation by analogy may be Permian. The Badito formation may be equivalent to the Yeso formation, but is not lithologically typical.

This area was probably relatively close to the eastern margin of the trough because these formations thin very rapidly to the east by overlapping the Precambrian rocks. On the north side of Red Canyon, the red beds between the Precambrian and the Entrada thicken toward the west at the rate of 135 feet vertically in 375 feet horizontally. Most of the thickening is in the Sangre de Cristo formation. If this rate of thickening continues westward under Wet Mountain Valley, a thickness of 10,000 feet would be attained about 5 miles west of the outcrop.

Northern Sangre de Cristo Range

The northern part of the Sangre de Cristo Range lies between Huerfano Park and the Arkansas River. It is composed chiefly of Permo-Pennsylvanian strata, some of which have been strongly metamorphosed and faulted. The central core of the range consists of an anticline in which the lowest Pennsylvanian strata are deformed and even rendered schistose by injective folding (Burbank and Goddard, 1937). This central core does not necessarily coincide with the crest of the range. The many faults subparallel to the axis of the range make correlation difficult.

The Permo-Pennsylvanian section between Crestone, Sagauche County, and Westcliff, Custer County, has three general lithologic units. The lowest is fine-grained dark greenish-gray sandstone, dark-gray silty shale and some beds of limestone, and a minor amount of dark greenish-gray conglomerate with pebbles up to 2 inches in diameter. This unit is about 3000 feet thick but is distorted and metamorphosed. Probably some of the shale at the base of this unit is equivalent to the Kerber formation. It may also contain some of the Clastic member of the Sandia formation, although the writer did not identify it. The upper part of the lower unit may be equivalent to the Madera formation because it contains crinoid stems, *Dictyoclostus* sp., *Hustedia mormoni*, *Spirifer rockymontanus*, and *Composita* sp. in a bed of slightly metamorphosed light-gray sandstone about 10 feet thick, on the west side of the divide about 300 yards north of Venable Pass at approximately the same elevation as the Pass (Silesia Peak quadrangle, U. S. Forest Service). Pennsylvanian Foraminifera, corals, Bryozoa, and brachiopods occur west of and a little north of Comanche Lakes (Johnson, 1929).

The middle unit, estimated as at least 2000 feet thick, consists of grayish-red, fine-grained sandstone interbedded with light greenish-gray coarse-grained conglomeratic sandstone and thin beds of limestone. The pebbles in the conglomerate beds in this unit are somewhat larger than those in the lower unit. *Fusulina distenta* occurs in a fragment of gray limestone enclosed in a bed of grayish-red arkosic conglomerate which crops out a few hundred feet above timber line on top of the divide between Goodwin and Venable creeks. The specimen is unique and whether it was in a pebble derived from a pre-existing limestone or is a fragment from a local limy bed that was reworked by wave action before it was lithified is a moot question. Limestone fragments in this conglomerate have grains of quartz imbedded in their surfaces which suggests that they represent fragments of a bed reworked before it was entirely lithified. This bed lies on the east side of

the core of the range and is separated from the lower unit by one or more large faults, so its position in the section is not known. On the basis of lithology it and the surrounding beds are tentatively placed near the top of the middle unit.

The upper unit consists of grayish-red and brownish-gray conglomerate in which the boulders of igneous and metamorphic rocks average about a foot in diameter, and range up to 6 feet in diameter. Massive beds of conglomerate are separated by thin layers of red and gray sandstone, siltstone, or shale and seem to be very coarse piedmont cyclothems. More or less continuous exposures up to 3000 feet are visible, but the total thickness may be much greater. This is the Crestone conglomerate phase of the Sangre de Cristo formation which correlates with the conglomeratic upper red beds in the Arkansas River valley farther north, and with the Sangre de Cristo formation in the Culebra Range to the south.

Melton (1925b) also recognizes three lithologic divisions in the Sangre de Cristo formation. Undoubtedly the upper two correspond roughly to those of the present writer. Melton's lowest unit, the Veta Pass limestone member of the Sangre de Cristo formation, was named in an area where the basal dark shale of the Kerber formation is absent, and therefore is probably equivalent to the upper part of the lowest unit of the present writer. The middle division of Melton is called the lower Sangre de Cristo formation and is 7500 feet thick. The upper division called the upper Sangre de Cristo formation, which contains the Crestone conglomerate phase, is 5500 feet thick east of Crestone.

A thick section of Permo-Pennsylvanian strata lies on the east slope of the range west of the village of Hillside. Near the crest of the range, these strata have been slightly metamorphosed, and their color has been altered. A zone of five limestone beds crosses the valley of Lake Creek just west of the Cloverdale mine. This zone of limestone can be traced southward into the cirque at the head of North Brush Creek. At this locality the limestone is more sandy than it was on Lake Creek and contains *Spirifer* sp., *Schizodus* sp., *Domatoceras* sp., and a straight nautiloid cephalopod. The limestone is not oölitic. The limestone is separated from the Precambrian by faults and intrusive porphyry so its stratigraphic position is not known. There is a faint suggestion that this zone may be equivalent to the Whiskey Creek Pass limestone because it is the highest fossiliferous bed in the section and it lies several hundred feet below the base of the grayish-red and brownish-gray clastic strata. It may possibly be equivalent to the gray calcareous beds in the Arkansas River detailed section (Intervals 219–230). The fauna and lithologic characteristics of the two beds are different, but both are the highest beds in their respective areas containing marine invertebrates.

Arkansas River Area

Description.—A detailed section of the Late Paleozoic strata was measured in the Arkansas River valley and its tributaries between Wellsville and Howard, Fremont County, Colorado. The section, the top of which is truncated by a fault, is 13,170 feet thick. It consists mainly of red coarse-grained clastic sedimentary rock. The strata dip as much as 30° E., and the horizontal distance between the top and bottom of the section is about 5 miles. This section lies near the eastern margin of the trough, and the strata probably overlap against the former margin of the trough, so that the strata today may appear thicker than the vertical thickness of the strata when deposited. The writer has divided this section into three formations: the Kerber at the base, the Minturn, and the Sangre de Cristo at the top.

Pennsylvanian.—The Kerber formation in the vicinity of Wellsville rests unconformably on the Leadville limestone. It consists of about 200 feet of dark-gray illitic shale, brown sandstone, and thin seams of coal. No marine fossils have been found in these beds which are almost identical lithologically with the type Kerber in the Bonanza district. On Taylor Creek, 2 miles southeast of Wellsville, the base of the section consists of unfossiliferous limestone and medium-gray shale. No fault seems to lie between the Mississippian and Pennsylvanian here. If this contact is unconformable, a marked overlap takes place toward the southeast. The writer found no other outcrop of the basal

Pennsylvanian farther southeast in this area. The age of the Kerber formation is not known. It may be Morrowan or Atokan.

The Minturn formation overlies the Kerber in this area and is about 4200 feet thick. In the base of the Minturn formation at Wellsville about 600 feet of red sandstone and shale is interbedded with gray fossiliferous limestone and shale. About 200 feet above the base of this unit a dark muddy shale (Interval 36, Arkansas River section) contains:

Plectogyra sp. 15% of fauna
Crinoid plates
Echinoid spines
Derbyia crassa (Meek and Hayden) 2%
Linoproductus sp. 26%
Composita sp. 5%
Aviculopecten sp. 3%
Annuliconcha sp. 1%
Straparollus catelloides ? (Conrad) 2%
the following ostracodes: 45%
Jonesina arcuata Harlton
Sulcella sulcata Coryell and Sample
Hastifaba pervulata Cooper
Bythocypris sp.
Cavellina cf. *C. pulchella* Coryell

The ostracodes were identified by Mrs. Betty Kellett Nadeau, who believes (personal communication) they are very Late Atokan or very Early Desmoinesian.

Henbest (1947) reports that *Millerella* occurs in the Belden formation in this area. A description of the locality (Henbest, personal communication, March 8, 1951) indicates that the nodular limestone in Interval 46 (Arkansas River section) is the *Millerella*-bearing layer. This bed seems to lie about 295 feet above the base of the Minturn formation.

This zone of gray limestone at the base of the Minturn formation is probably equivalent to the Shale and Limestone member of the Belden formation in western South Park and occurs also in the base of the Minturn formation in the Bonanza district. It is possibly equivalent to the upper part of the Clastic member of the Sandia formation which is Late Atokan. The fauna of this limestone zone and of the upper Belden formation is a mixture of Late Atokan and Early Desmoinesian and may represent a transition between the two epochs. Brill (1950) suggested that this zone correlated with the Gray limestone member of the Madera formation, but probably it is older.

Overlying this zone of limestone is about 1200 feet of sandstone of which the lower part is red and the upper part grayish green. Thin beds of limestone are interbedded with clastic strata. One bed of limestone (Interval 147) contains *Myalina cuneiformis*. White (1915) reports a Pottsville coal flora 900 feet above the base of the red beds. Probably this flora came from the strata between Intervals 90 and 100 (Arkansas River section), depending on what bed is chosen as the base of the red beds.

Overlying this clastic unit is about 450 feet of gray sandstone and shale, black shale, dolomite, and gypsum. The gypsum crops out in the hills northeast of Swissvale switch and south of the Arkansas River on tributaries of Taylor Creek. It is cut out by a fault in the valley of the river. North of the Arkansas River a thick bed of black shale lies about 125 feet below the gypsum. On Hayden and Big Cottonwood creeks near Coaldale, about 10 miles to the southeast, the dolomite and black shale lie several hundred feet below the main mass of the gypsum. On Big Cottonwood Creek, some of the dolomite is sandy and contains Pennsylvanian brachiopods and cephalopods. The gypsum cannot be traced continuously through the area. It may rise in the section toward the southeast or it may have been injected between different beds in different parts of the area. The writer proposes the name Swissvale gypsum member of the Minturn formation. It is named for exposures about a fourth of a mile northeast of Swissvale switch (Denver and Rio Grande Western Railroad), Fremont County, Colorado.

The gypsiferous sequence is overlain by about 1850 feet of red sandstone and conglomerate interbedded with thin gray shale and limestone. The top of this unit consists of about 200 feet of gray shale and limestone (Intervals 219–230) which crops out on top of the tunnel on the railroad. Interval 220, about 4300 feet above the base of the Pennsylvanian section, contains a molluscan fauna. The pelecypods, according to Dr. N. D. Newell (Personal communication, Dec. 7, 1950), "resemble somewhat the Lower Permian *Bakewellia parva*. . .shells of this general type, however are fairly common in the late Paleozoic from the Mississippian on and I would not place much reliance on this form". Two genera

of high-spired gastropods were examined by Dr. J. B. Knight, who states (personal communication) that one is *Stegocoelia* sp. which ranges throughout the Permo-Carboniferous, and the other is a new genus he has seen in the Big Saline group of Texas. These are the highest marine invertebrate fossils found in the area. Throughout the middle part of the trough, the highest marine invertebrate fossils seem to be of Desmoinesian age, therefore it may be reasonable to assume that these fossils are also Desmoinesian.

The writer has chosen the top of this zone of gray shale and limestone as the top of the Minturn formation. Possibly it is equivalent to the Whiskey Creek Pass and Jacque Mountain limestones. This is suggested by the position of the zone above the gypsum and the fact that it is the highest bed containing marine fossils.

According to White (1915) a flora which "leaves little doubt as to the Permian age of its horizon" was collected "near the south portal of the tunnel at Swissvale". The general trend of this section of the railroad is southeast, so perhaps White made the collection near the eastern portal; however the bearing of the tunnel is N. 85° E., therefore the "south portal" would be the west end. Plant remains are common in this part of the section, and it is not clear whether this flora lies above or below the fossiliferous limestone zone. Perhaps this flora is Permian; on the other hand, of seven genera and six species listed by White, three genera and one species have been found in rocks of Pennsylvanian age (Moore *et al.*, 1936; Donner, 1949).

Permian (?). — The Permo - Pennsylvanian boundary is not clearly established. Possibly it lies somewhere in the lower part of the Sangre de Cristo formation; on the other hand all the red beds may be Pennsylvanian. The Sangre de Cristo formation overlies the fossiliferous limestone zone and consists of about 8800 feet of red and grayish-red sandstone and conglomerate with thin bands of gray nodular limestone. Much of the formation is made up of cyclothems which begin with beds of conglomerate and grade upward into finer-grained clastic rock and have nodular limestone as the top member. This part of the section is probably equivalent to the Crestone conglomerate phase. The top of the formation is faulted against the Precambrian granite.

Bones of pelycosaurs and of the cotylosaur *Didactes* sp. occur in a greenish-gray shale along with scales of ganoid fish. This bed (Interval 300) lies 1453 feet above the base of the formation and about 5786 feet above the base of the section. The bones were identified by Dr. J. M. Wilson and Dr. T. E. White. These reptiles occur in the red beds of Kansas, Oklahoma, Texas, and New Mexico. Pelycosaurs have been reported from the Cisco and Wolfcamp of Texas (Romer and Price, 1940); however, Cheney (1947, p. 207) has placed all the reptile-bearing Cisco rocks in the Wolfcamp. Cotylosaur bones are possibly associated with *Spirifer rockymontanus* in Rio Arriba County, New Mexico (Williston and Case, 1912). The writer has assigned the Sangre de Cristo formation to the Wolfcampian because of these reptile bones.

Bonanza District

The Pennsylvanian section in the Bonanza district was described by Burbank (1932) and discussed by Burbank and Goddard (1937). The basal dark shale was named the Kerber formation, the overlying coarse clastic strata was assigned to the Maroon formation, and the Rico formation was recognized at the top. The present writer believes that the Kerber formation and the Minturn formation are present here.

The Kerber formation consists of about 200 feet of dark-gray shale and brown sandstone with a few seams of impure coal. It is nonmarine and resembles the Kerber formation at Wellsville, 25 miles to the northeast. It seems to resemble the basal few hundred feet of the poorly exposed Garfield formation in the Monarch district. The writer has assumed that the Kerber is Morrowan in age; however, it may be younger.

The Minturn formation is faulted and partly covered. A section on Kelly Creek seems to be about 1700 feet thick; however, Burbank and Goddard (1937) believe the section is faulted and may be more than 3400 feet thick. A zone of limestone interbedded with red sandstone lies near the base of the Minturn formation.

This zone is equivalent to limy beds in the base of the Minturn formation at Wellsville and at Monarch. A collection from a gray shale about 150 feet above the base of the formation where an irrigation ditch leaves Kelly Creek contains:

Lingula carbonaria Shumard 2% of fauna
Schizophoria schucherti Girty 2%
Linoproductus inornatus King 25%
Composita subtilita (Hall) 9%
Nuculana bellistriata ? (Stevens) 4%
Pseudorthoceras knoxense (McChesney) 2%
Soleniscus sp. 2%
the following ostracodes: 45%
Jonesina arcuata Harlton
Jonesina cf. *J. biformis* Bradfield
Sulcella sulcata Coryell and Sample
Coryellites cf. *C. bisoni* Wilson
Cavellina sp.

This ostracode fauna is somewhat similar to that found in Interval 36 of the Arkansas River section. A gray shale with limestone nodules lies on a hogback about half a mile east of Kelly Creek more than 1250 feet above the base of the Minturn formation. This bed contains:

Crinoid columnals 4% of fauna
Linoproductus inornatus King 53%
Spirifer opimus Hall 5%
Allorisma granosum Shumard 18%
Nuculana bellistriata (Stevens) 5%
Aviculopecten sp. 5%
Bellerophon crassus Meek and Worthen 5%
Soleniscus sp. 5%

Burbank (1932, p. 14) reports the presence of *Chaeteles milliporaceous* about half way up in the formation.

The writer was not able to recognize the Rico formation (Burbank and Goddard, 1937, Pl. 2) in this area.

Red Gulch

A relatively small outcrop of late Paleozoic red beds occurs on the tributaries of Red Gulch about 6 miles north of Cotopaxi, Fremont County, Colorado. About 500 feet of red sandstone and conglomerate overlies the Leadville limestone. The top of the section is faulted against the Precambrian granite. These strata are entirely clastic and become increasingly conglomeratic toward the top of the section. Pebbles of brown and gray chert occur in the conglomeratic beds along with fragments of igneous and metamorphic rocks. The chert pebbles are more abundant in the upper part of the section, largely because the conglomerate is more abundant there. The chert was derived from the Mississippian limestone. It was not possible to correlate this section with the Arkansas River section about 8 miles west. Probably the Red Gulch section lay close to the eastern margin of the trough.

Western South Park

Description.—A large area of western South Park is underlain by late Paleozoic strata. Rapid lithologic changes make it difficult to correlate these beds from one part of the Park to another, and more difficult to correlate with areas outside the Park. The strata are as much as 13,000 feet thick, and all but the lower 1000 to 1700 feet are nonmarine. The writer proposes to divide the section into three formations: the Belden, Minturn, and Maroon.

Pennsylvanian.—The strata constituting the Belden formation were originally assigned to the Weber (?) formation by Johnson (1934) and Gould (1935). Stark *et al.* (1949) recognized three members of the Weber (?) formation—the lower Shale member, the middle Shale and Limestone member, and the Coffman conglomerate member, all assigned to the Pottsville.

The Shale member consists of 100–300 feet of dark-gray shale and sandstone with seams of impure coal. It contains plant remains and a few marine invertebrate fossils (Johnson, 1934). This member seems to be equivalent to the Kerber formation of the Arkansas River section and the Bonanza district.

The middle Shale and Limestone member consists of 1000–1400 feet of dark shale, brown sandstone, and gray limestone. Numerous fossils were found by Johnson (1934) on Trout Creek. East of Coffman Ridge, the writer obtained *Chonetes* cf. *C. dominus*, *Marginifera ingrata*, and *Spirifer rockymontanus* from Bed No. 3 (Stark *et al.*, 1949, p. 150). In the dark shale near the top of the member, *Jonesina arcuata* is abundant in a few thin beds (Stark *et al.*, 1949, Bed No. 3, p. 150). The Newett limestone (Gould, 1935) and other limestone beds in the lower part of the member are

equivalent to the zone of limestone at the base of the Minturn formation on the Arkansas River and at Bonanza. Facies change will account for the lithological differences between these two sections. The writer has assigned these two members of the Weber (?) formation to the Belden formation.

The Coffman conglomerate, originally defined as a member of the Maroon formation (Gould, 1935), was made a member of the Weber (?) formation by Stark *et al.* (1949). It consists of 20–1000 feet of gray arkosic sandstone and quartz-pebble conglomerate. The contact between the conglomerate and the underlying Shale and Limestone member of the Belden formation is gradational. The Coffman conglomerate seems to be a local nonmarine deltaic deposit which thins northwestward from 1000 feet to about 20 feet in about 4 miles (Gould, 1935). The writer believes that on lithologic grounds the member belongs in the Minturn formation rather than in the Belden.

Stark *et al.* (1949) divided the Maroon formation into two members, the Chubb siltstone and Pony Spring siltstone (Gould, 1935). In the writer's opinion the Chubb and the lower part of the Pony Spring is equivalent to the Minturn formation. The Chubb siltstone member consists of 1200–1800 feet of gray and reddish-brown siltstone and shale. It contains a few plant remains and is probably mainly nonmarine. Evaporite is widespread in the Chubb member in the northwestern part of the Park (Stark *et al.*, 1949, p. 154, 156). In the type section, a cavernous, greasy-looking, light-colored soil occurs about 110 feet above the base of the member. This type of soil is commonly associated with gypsum bedrock in other parts of the state. Although no outcrop occurs here, gypsum is probably present at depth. A considerable thickness of distorted gypsum occurs in the Chubb member on the north side of West Hall Butte (sec. 27, T. 21 S., R. 77 W.). The salt which occurs in the drainage of Salt Creek is probably of the same age. The gypsum in the Chubb member is possibly equivalent to the Swissvale gypsum member of the Minturn formation, and if so, other beds may also be equivalent. In the type section of the Chubb, several thin beds of limestone underlie the gypsum. Thicker beds of limestone occur in about this same stratigraphic position 4 miles to the southeast on an abandoned railroad grade. The gypsum is not visible at this locality. In the Arkansas River section, beds of dolomite are present above and below the gypsum. Possibly these zones of carbonate rock are equivalent.

The writer assumes that the Chubb siltstone member of the Minturn formation is Desmoinesian because of its position in the section. Stark *et al.* (1949) state that it is probably Permian but may be at least partly upper Pennsylvanian.

The Pony Spring siltstone member overlies the Chubb member. It consists of 4000–6000 feet of greenish-gray and red siltstone and sandstone and was deposited in piedmont cyclothems. The contact of the Minturn and Maroon formations lies in the lower Pony Spring member. It is at the top of a limy zone a few hundred feet above the top of the Bath sandstone (Gould, 1935). This zone consists of gray shale and thin beds of limestone on Salt Creek. It can be traced southward to Muleshoe Gulch where the limestone is much thinner. This zone lies about 2700 feet above the gypsum and about 4300 feet above the base of the Pennsylvanian. This zone is tentatively correlated with the Jacque Mountain-Whiskey Creek Pass limestones (Pl. 1).

The Jacque Mountain limestone crops out on Hoosier Ridge about 10 miles north of Alma, where it forms the base of the Upper division of the Maroon formation (Singewald, 1942; 1947). It consists of a gray oölitic, sandy limestone about 20 feet thick, and lies about 5500 feet above the base of the section (Singewald, 1942). The writer believes the section may be somewhat thinner. A probable equivalent of this bed, not lithologically typical of the Jacque Mountain limestone, crops out farther south on the divide between Beaver and Crooked creeks (Singewald, 1942, p. 11), about 22 miles north of Salt Creek where the limy zone occurs in the basal Pony Spring member. This correlation is readily open to question, but correlation charts by Singewald (1942, p. 7) and Stark *et al.* (1949, Pl. 8) agree with the writer's conclusion that such a correlation is reasonable.

If this correlation is correct, the basal Pony Spring siltstone is probably Desmoinesian. The Bath sandstone (Gould, 1935), at the base

of the Pony Spring, consists of about 800 feet of greenish-gray sandstone. It was assigned to the Permian on the basis of *Walchia piniformis*, *W. gracilis*, *Voltzia*, and *Ulmannia*, which according to Stark *et al.* (1949, p. 46) are "unknown from the Pennsylvanian anywhere". These plants do occur in the Permian strata at various places in the United States, but they probably indicate certain ecological conditions rather than any interval of time. *Walchia pinniformis* occurs in the *Wedekindellina-Fusulina* zone at McCoy (Donner, 1949), and *Voltzia* and *Ulmannia* occur in the Missouri series of Kansas (Moore *et al.*, 1936). This flora can no longer be considered diagnostic of the Permian period.

Permian (?).—A small freshwater fauna occurs in the dark shale beds on the north side of Salt Creek (Division 4 of Gould, 1935, p. 990). Dr. N. D. Newell states that the pelecypods are closely related to *Carbonicola*, although they may not belong to that genus (Personal communication, Dec. 7, 1950). Presumably they are either Pennsylvanian or Permian. The ostracodes were identified by Mrs. Betty Kellett Nadeau as *Carbonita* (?) *tumida magna*. This variety occurs in the Missouri, Virgil, and Wolfcamp of Kansas (Kellett, 1935, p. 161). This fauna lies about 1800 feet above the base of the Pony Spring member and is in the Maroon formation. It may be coeval with the reptile-bearing bed in the Arkansas River section. It is assumed to be Wolfcampian, but may be older.

The upper part of the Pony Spring siltstone is probably equivalent to the siltstone and fine-grained sandstone in the upper red beds on Frying Pan and Woody creeks in Eagle and Pitkin counties. The writer (1944, Fig. 4) erroneously assigned the strata to the State Bridge formation, but they are for the most part older than State Bridge.

Cyclic sedimentation, characteristic of the upper red beds in the trough, is common in the Pony Spring member. This and its stratigraphic position suggest correlation with the Sangre de Cristo formation farther south.

McCoy Area

Description.—The McCoy area lies in northern Eagle and southern Routt counties, Colorado. The Permo-Pennsylvanian strata are divided into the McCoy formation (Roth, 1930), the Maroon formation, the Schoolhouse tongue of the Weber sandstone (Murray, 1949), and the State Bridge formation (Brill, 1942).

Pennsylvanian.—The McCoy formation consists of those sediments between the Mississippian limestone and the top of the Jacque Mountain limestone. The lowest fossiliferous bed is a green micaceous shale (Unit 12, Donner, 1949) immediately beneath the bed from which Roth and Skinner (1930, p. 336) made collection No. 183. It contains fusulinids close to if not identical with *Fusulina pristina*. This species occurs also in the basal part of the Youghall formation in Moffat County (M. L. Thompson, 1945). The zone of *Wedekindellina-Fusulina* lies between 1978 and 2177 feet above the base of the formation (Donner, 1949).

A bed of gray limestone 4 to 8 feet thick (Unit 93, Donner, 1949) lies 2927 feet above the base of the formation. The writer believes that this is equivalent to the Jacque Mountain limestone. This bed is neither oölitic nor fossiliferous, but it is relatively thick and is the highest carbonate bed of any significance. The closest outcrop of typical Jacque Mountain limestone occurs east of the Piny River about 10 miles southeast of the McCoy area. The McCoy formation is equivalent to the Minturn and Youghall formations.

Permian.—The Jacque Mountain limestone is overlain by 665 feet of coarse-grained, unfossiliferous red beds which the writer proposes to assign to the Maroon formation. Lithologically they are indistinguishable from the red beds below the Jacque Mountain limestone, and they may be older than Permian.

Murray (1949) showed that the State Bridge formation (Phosphoria) was underlain by an unconformity. He found 59 feet of the Schoolhouse tongue of the Weber sandstone between the Maroon formation and the State Bridge formation on the west side of the McCoy area and none on the east side.

The State Bridge formation overlies the Schoolhouse tongue of the Weber sandstone in this area. It consists largely of red and yellow siltstone. A small fauna occurs in a limestone near the base (Brill, 1942). This limestone is probably equivalent to the South Canyon dolomite member of the Maroon formation

TABLE 1.—PERCENTAGE OF INDIVIDUALS IN COLLECTIONS OF PENNSYLVANIAN FOSSILS

Section and lithology	Foraminifera	Stromatoporoids	Corals	Crinoids	Echinoids	Bryozoans	Brachiopods	Pelecypods	Gastropods	Cephalopods	Trilobites	Ostracodes	Fish teeth
Minturn formation:													
Bonanza section (Int. 25). Gray shale and nodular limestone							38	4	2	2		54	
Bonanza section (Int. 45). Gray shale and nodular limestone				4			58	28	10				
Arkansas River section (Int. 36). Dark-gray shale and limestone	15			2			33	3	2			46	
Arkansas River section (Int. 42). Reddish-brown shale and gray nodular limestone						1	44	3	1		1		
Clastic member of Sandia formation:													
Whiskey Creek Pass (Int. 14). Dark-gray muddy shale						7	58	10	4	1	1		
Whiskey Creek Pass (Int. 18). Sandy limestone and gray shale							23		77				
Pecos (Int. 51). Black limestone							98	2					
Pecos (Int. 61). Gray finely crystalline limestone							100						
Gray limestone member of Madera formation:													
Whiskey Creek Pass (Int. 28). Muddy limestone							89	7	4				
Whiskey Creek Pass (Int. 33). Dark-gray micaceous shale							92	8					
Gallinas River (Int. 31). Gray limestone	60						40						
Gallinas River (Int. 32). Gray limestone			100										
Gallinas River (Int. 44). Calcareous shale and gray limestone	3		18				73	3	3				
Pecos (Int. 72). Gray finely crystalline limestone							100						
Pecos (Int. 93). Dark-gray calcareous shale						10	87	3					
Arkosic limestone member of Madera formation:													
Greasier Creek (Huerfano Park). Gray calcareous shale			2	1		16	53	5	1				
Whiskey Creek Pass (Int. 86). Black silty shale							20	80					
Whiskey Creek Pass (Int. 124). Gray silty shale and muddy limestone							80		6	3			10
Whiskey Creek Pass (Int. 139). Dark-gray siltstone									100				
Whiskey Creek Pass (Int. 145). Gray shale and brown siltstone			37		13		31		18				
Whiskey Creek Pass (Int. 182). Dark-gray silty shale						18	37	6	32	6			

TABLE 1.—*Continued*

Section and lithology	Foraminifera	Stromatoporoids	Corals	Crinoids	Echinoids	Bryozoans	Brachiopods	Pelecypods	Gastropods	Cephalopods	Trilobites	Ostracodes	Fish teeth
Moreno Valley (Int. 29). Gray sandy limestone			5				90				5		
Moreno Valley (Int. 39). Dark-gray shale			1				93		4	1			
Moreno Valley (Int. 68). Grayish-brown sandstone							6	59	34				
Mora River (Int. 139). Gray coarsely crystalline limestone			3			12	85						
Mora River (Int. 153). Dark-gray shale and thin-bedded limestone	2	19					42	8	24	2			4
Gallinas River (Int. 82). Gray calcareous shale	40		6				54						
Gallinas River (Int. 110). Sandy limestone			66				33						
Pecos (Int. 183). Gray calcareous sandstone							72		28				
Pecos (Int. 203). White sandy limestone			10			24	36	30					
Same bed, 2 miles south							65	23	11				
Pecos (Int. 222). Brown calcareous silty shale						2	29	54	14				
Pecos (Int. 229). Gray siltstone							100						

(Bass and Northrop, 1950) and therefore of Phosphoria age.

FAUNAL PECULIARITIES

Marine invertebrates could enter the trough only from the two ends, therefore topographic and ecologic barriers within the trough could readily influence the distribution of the faunas. The *Millerella* fauna occurs mainly in the northern end of the trough. The Desmoinesian *Fusulinella* zone is associated only with the Hell's Canyon formation at the extreme northern end of the trough. Fusulinellas of this type occur in the northern mid-continent region and in north-central Utah. In late Atokan or early Desmoinesian time, a megafauna migrated into the southern part of the trough from Texas. The species of Cherokee Fusulinas is different in the northern and southern parts of the trough. Either these species migrated in from different ends of the trough, or the bottom ecology in the two areas was different enough to cause the species to differ.

At various times the trough may have been similar to a strait or an estuary, but its shape seems to have little influence on the character of the fauna.

Table 1 shows the percentage of individuals in each of the various groups of marine animals in 33 collections, ranging from 10 to 70 specimens each. The fauna is fairly representative for each locality. The fossils are all of Atokan and Cherokeean age and come from the Minturn and Madera formations and from the Clastic member of the Sandia formation. The numbers of individuals of brachiopods average about 60 per cent of the faunas and, of the brachiopods, productids are the most common type. Gastropods and pelecypods are second and third in order of abundance. As might be expected these two groups are mainly in the sandy and silty beds, although there are some exceptions. Corals are most abundant

in pure limestone, but several collections from beds of sandy limestone contain both solitary and colonial corals. *Chaetetes* is very common in the trough, and large colonies seemed to thrive where grit was being deposited. They have been observed in the Minturn formation and Arkosic limestone member of the Madera formation.

Traces of original color has been found in a few fossils. *Marginifera ingrata* and some specimens of *M. muricatina* are dark red. This color does not appear in these species at all localities but seems to be present in specimens enclosed in dark muddy limestone or dark calcareous shale. This color was probably not derived from the surrounding sediment, and therefore it may be the original color of the shell.

Pelecypods that show original color occur in the Arkosic limestone member of the Madera formation in the Pecos section. Pectinoid forms have broad bands of alternating light and dark color radiating from the beak. Pleurophoroid types are speckled with small dark spots.

Geologic History

Pre-Pennsylvanian

The Ancestral Rockies are believed to have been positive areas during much of Paleozoic and Mesozoic times (Lovering, 1929; Lovering and Johnson, 1933). The Cambrian, Ordovician, Devonian, and Mississippian formations are separated by angular unconformities where they wedge out against the Front Range highland. This indicates that this highland, at least, was periodically uplifted during the Paleozoic era.

The Mississippian limestone is the most widespread pre-Pennsylvanian formation in the vicinity of the Ancestral Rockies. In some areas, pebbles of Mississippian chert (marked in Pl. 2 as "pebbles") occur in Pennsylvanian strata several hundred feet above the base of the section. This suggests that the Mississippian chert-bearing limestone was much more widespread than its present area of outcrop would indicate.

During late Mississippian and (or) early Pennsylvanian time, karst topography developed on the pre-Pennsylvanian limestone surfaces in parts of Missouri, Kansas, South Dakota, Wyoming, Arizona, and Colorado. Caves, sinkholes, natural bridges, and other solution features are common in central Colorado (Brill, 1944; Donner, 1949).

Pennsylvanian

General statement.—The depositional history of the zeugogeosyncline is typical. It began with the deposition of dark shale, limestone, and coal in a mildly unstable basin. The deposition of the Gray limestone member of the Madera formation marked a period of stability, which was followed by increasing instability in the trough and neighboring highlands. This is reflected in the deposition of wedge arkose and thin marine limestone along the eastern margin of the trough. During a part of this time evaporite was accumulating in the middle and near the western margin of the northern end of the trough. Following the deposition of the evaporite wedge, arkose entered the trough from both sides in increasing quantities until the marine waters were excluded and the entire trough filled with alluvium.

Morrowan time.—Apparently the Morrowan sea advanced northward through central and northwestern New Mexico and into Utah on the west side of the Uncompahgre highland and entered the zeugogeosyncline in northwestern Colorado (Fig. 2). As the neighboring highlands were gently uplifted, the residual soil was eroded and transported into the subsiding trough. The dark-gray illitic shale was deposited in mud flats and coal swamps on the margins of the trough while the solution load was precipitated as muddy limestone in the deeper portions of the trough. That the Front Range highland was uplifted somewhat more than the Uncompahgre highland is suggested by the increase in nonclastic sediment from east to west across the trough. The marine limestone containing the zone of *Millerella* is present from Moffat County south as far as Glenwood Springs. Southeastward the Belden formation becomes increasingly nonmarine. In the Arkansas River area and the Bonanza district, it is apparently entirely nonmarine. The Belden-Kerber formation crops out as far

south as Huerfano Park. It seems to have about the same areal distribution as the underlying Leadville limestone. The Morrowan sea retreated toward the northwest; however, the deposition of nonmarine dark shale may have continued into Atokan time.

Atokan time.—The late Atokan sea entered the trough from the south and extended as far north as central Colorado (Fig. 3). No Atoka strata occur in northwestern Colorado. At this time, the neighboring highlands began to rise more rapidly and to furnish coarse clastic sediment to the flanks of the trough. While the coarse sediments were being deposited on the flanks, dark shale and limestone were being deposited in the center. The Clastic member of the Sandia formation which lies in the southern part of the trough is probably equivalent to the upper Belden formation and lower Minturn formation at some localities in central Colorado. The Shale and Limestone member of the Belden formation in western South Park interfingers with arkosic sandstone in the Arkansas River area.

The Glen Eyrie formation of eastern Colorado is probably older Atokan than any of the deposits in the zeugogeosyncline. The strata in the trough contain a mixture of Atokan and Desmoinesian faunas. Many fossils normally associated with the Desmoinesian of the mid-continent region occur in the zone of *Fusulinella* in the trough. If the lower part of the Belden formation is late Morrowan and the upper part is late Atokan, the early Atokan must be represented by an interval either of nondeposition or erosion. No evidence of an unconformity has been seen in the formation.

Desmoinesian time.—During early Cherokeean time, a seaway with specialized species of *Fusulinella* entered the northern end of the trough. These fusilinids are found in northern Utah, in the Hartville uplift, and in the Black Hills, and presumably represent a fauna that did not inhabit the southwestern United States.

In Cherokeean time in the southern part of the trough, the adjacent highlands were more or less stable, and the bulk of the sediment deposited in the trough was calcareous. The Gray limestone member of the Madera formation which contains the zone of *Wedekindellina* was deposited at this time. At about this same time, coarse clastic sediments with thin beds of marine origin were being deposited in the northern end of the trough. *Fusulina pristina* occurs in some of these marine beds. The zone of *Wedekindellina* in the northern part of the trough lies rather high in the Minturn and McCoy formations and is not associated with such thick deposits of limestone as it is farther south.

During the early Desmoinesian, gypsum and some salt were deposited in lagoons or shallow basins in the middle of the trough. Salt and gypsum formed in the basin west of the Uncompahgre highland at about the same time (Fig. 4).

In late Cherokeean time, the highlands were uplifted spasmodically. The uplift is reflected in the cyclothems in the Arkosic limestone member of the Madera formation and in the upper Minturn formation. In some of the marine layers which are interbedded with the clastic sediment, *Fusulina* is common. The Jacque Mountain and Whiskey Creek Pass limestones were deposited during a time of relative stability late in Cherokee time.

Strata of Marmatonian age have been found in southwestern Colorado and in eastern Colorado, but no marine Marmaton has been found in the trough.

Missourian and Virgilian time.—The late Pennsylvanian seaway moved northward from central New Mexico and entered the south end of the trough. *Triticites* of Missourian and Virgilian age occur at Pecos, New Mexico, but have not been found farther north. Either the upper Pennsylvanian strata become nonmarine red beds farther north or they are absent through erosion or nondeposition. Possibly the trough was uplifted during late Pennsylvanian, and little or no deposition took place at this time.

Wolfcampian time.—It is assumed that most of the Sangre de Cristo and Maroon formations are Wolfcampian, through the fossil evidence is very meager. During Wolfcampian time, the highlands were uplifted spasmodically and rapidly. The sea was excluded from the trough, and the deposits consisted of piedmont type of cyclothems formed on flood plains and alluvial fans. Probably numerous lakes and

swamps formed in the center of the trough, and these were drained by rivers flowing southward. Several deposits containing fresh-water fossils occur in South Park. The bones of aquatic reptiles occur with fish scales in Fremont County, Colorado. These reptiles are not found north of this locality in Colorado but are common in Oklahoma and New Mexico; therefore the waterways up which the reptiles travelled must have flowed southward. The flora in these strata is mainly of a dry-soil type and further suggests an alluvial fan environment.

Leonardian time.—By the close of Wolfcampian time the highlands and trough may have been eroded to a common level. During most of Leonardian time, this region stood above sea level and was more or less stable.

In early Leonardian time the Yeso formation was deposited in the southern end of the trough. The red siltstone and fine-grained sandstone of the Yeso suggest that the source area was either low-lying or remote. Beds of gypsum and a pelecypod fauna in one of the thin beds of limestone indicate that shallow marine waters extended this far north.

The writer's reconstruction of conditions in the late Leonardian is contingent on the equivalence of the Lyons sandstone, the Glorieta sandstone, and the Schoolhouse tongue of the Weber sandstone (Fig. 5). During later Leonardian time the exposed arkosic strata were severely weathered producing a clean white sand. Persumably this sand was transported to the flanks of the Ancestral Rockies where it accumulated as a beach and dune sand. In the trough, the Schoolhouse tongue of the Weber sandstone extended at least as far south as Eagle County, Colorado, and the Glorieta sandstone extended at least as far north as Colfax County, New Mexico.

Guadalupian time.—Following Leonardian time the highlands were uplifted somewhat, producing the red siltstone and fine-grained sandstone of the State Bridge formation. The northern end of the trough was depressed below sea level, and marine or brackish-water deposition extended as far south as Eagle County, Colorado. This was probably the feather edge of Phosphoria deposition in the vicinity of the Ancestral Rockies. Possibly the red beds in the Limestone member and Upper member of the San Andres formation are about the same age. If so, they indicate somewhat similar conditions in the southern part of the trough.

Conclusions

(1) The zeugogeosyncline of Colorado and northern New Mexico existed from Morrowan to Guadalupian time. The northern half of the trough developed in Morrowan time, the southern part in Atokan time. During Cherokeean time, the seas probably extended the entire length of the trough. The upper Pennsylvanian may be missing in most of the trough; however nonmarine strata assigned to the Wolfcamp may be upper Pennsylvanian entirely or in part.

(2) Four main stratigraphic units are recognizable: (a) the Belden and Kerber formations of Morrowan and Atokan (?) age; (b) the Clastic member of the Sandia formation of Atokan age; (c) the Minturn and Madera formations mainly of Cherokeean age; and (d) the Maroon and Sangre de Cristo formations mainly Wolfcampian (?).

(3) Four other stratigraphic units are confined to the ends of the trough: at the southern end of the trough, (a) the Yeso formation of Leonardian age, and (b) the San Andres formation of Leonardian and Guadalupian age; at the northern end of the trough, (c) the Weber sandstone of Pennsylvanian and Permian (?) age, and (d) the State Bridge formation of Guadalupian age.

(4) The Atokan and Desmoinesian faunas appear to be mixed in the upper Belden and lower Minturn formations. Cherokee megafossils occur with Atoka microfossils.

(5) Reptile bones occur in the Sangre de Cristo formation in the Arkansas River section. These are unique in the State of Colorado, but are numerous in the lower Permian of Texas, Oklahoma and New Mexico.

(6) An ecologic and topographic barrier was present in the trough in the vicinity of Custer and Huerfano counties, Colorado. This probably existed intermittently from Mississippian to Jurassic time. During the Pennsylvanian, it influenced the distribution of sediments and faunas in the trough. The Kerber

formation is not known south of Huerfano Park. The Clastic member of the Sandia formation is not known north of Huerfano Park. The zone of *Wedekindellina* seems to be missing in this area although it occurs at the northern and southern ends of the trough. The species of *Fusulina* north of this area are different from those south of it.

(7) A zone of limestone may be traceable for several hundred miles through the trough. In the northern part of the trough, it is known as the Jacque Mountain limestone member of the Minturn formation. In the southern end of the trough the writer has named it the Whiskey Creek Pass limestone member of the Madera formation. This zone has been used as a datum plane for correlations.

Detailed Sections

Pecos Section

Section of Permo-Carboniferous strata measured in the vicinity of Pecos, San Miguel County, New Mexico.

Top of section

Section ends on top of high peak on the north rim of Glorieta Mesa about 2 miles west of RR. station at Rowe.

Interval

		Feet	Inches
	San Andres formation: Upper member		
401.	Sandstone yellow, weathers darker, medium coarse-grained, subangular grains, noncalcareous, cross-bedded	10	
400.	Sandstone and conglomerate interbedded; sandstone yellow brown, weathers same, medium-grained, cross-bedded (foreset beds dip SW.); conglomerate, limestone matrix with small fragments of shale	10	
399.	Sandstone purplish gray, thin-bedded, medium-grained, cross-bedded	22	
398.	Conglomerate and sandstone brownish purple; conglomerate calcareous with rounded fragments of brown and pale-green shale up to ½ inch diameter; sandstone medium-grained, thin-bedded	7	
397.	Sandstone purple, medium-grained, thin-bedded near top	5	
396.	Partly covered; some shale blue green	5	
395.	Sandstone buff with large fragments of blue-green shale	1	
394.	Sandstone greenish gray near base, purplish gray above, medium-grained, cross-bedded (foreset beds dip SW.), calcareous	22	
393.	Conglomerate similar to Int. 391 grades up into Int. 394	1	
392.	Sandstone greenish gray, weathers brownish gray, medium-grained, scattered pebbles of green shale, grades up into Int. 393	1	
391.	Conglomerate grayish green, matrix mainly calcite, fragments of clay, limestone, potash feldspar up to ½ inch diameter; plant stems and bone fragments	1	8
390.	Sandstone similar to Int. 388	1	
389.	Conglomerate, matrix sandstone light gray, calcareous cement; fragments blue-green shale, brown algal? limestone and red siltstone, up to 1 inch diameter	1	
388.	Sandstone gray and pale purple, weathers grayish brown, cross-bedded, arkosic, calcareous	3	
387.	Shale and nodular limestone, maroon with gray bands, very irregular bedding	1	6
386.	Siltstone and shale interbedded in thick beds; dark red except upper 10–15 feet which is maroon; two bands of white siltstone 6–12 inches thick in basal 25 feet	77	
	Limestone member		
385.	Limestone pale purplish gray, weathers lavender, thin wavy bands of color suggesting algal deposit		6
384.	Siltstone brick red		6
383.	Sandstone white, weathers greenish white, fine-medium-grained		5
382.	Siltstone or very fine sandstone, brick red, mottled and banded with gray, calcareous. Strike, N.65°W. Dip, 4° S.	16	
381.	Covered	16	6
380.	Limestone pale brownish yellow, weathers same color, but cavernous, spongy appearance. Suggests gypsum cap rock	5	
379.	Limestone yellow brown, weathers same, thin-bedded, small subspherical masses of crystalline calcite on surface	6	
	Glorieta sandstone member		
378.	Covered; ledges of thin-bedded sandstone on slope	25	
377.	Sandstone white and yellow, weathers yellow, fine-grained, uniformly sized, rounded quartz grains, calcareous; sandstone breccia at base	150	
	Total thickness San Andres formation	383	1
376.	Covered; gray shale and pink siltstone in float	5	
375.	Covered; pinkish-red siltstone in float	38	

	Feet	Inches
374. Limestone light gray with small brown spots; very rough, cavernous surface	1	6
373. Limestone brownish gray, weathers gray; finely crystalline, in two beds; surface shows small brown spots	7	
372. Sandstone (80%) and shale interbedded white and purplish gray in streaks and mottlings; sandstone fine-grained	1	6
371. Covered except in upper 3 feet. Seems to be chiefly orange-brick red siltstone, soft, noncalcareous	34	
370. Limestone white and pale gray, upper, and lower 2 feet silty with small black spots, middle 1 foot clear gray limestone with drusy cavities; contains *Allorisma* sp. up to 5 mm. long	2	
369. Shale gray, silty, soft; thin curved lenses of finely crystalline gray limestone at top	1	4
368. Siltstone, sandstone, and shale interbedded, pale brick red; sandstone fine-grained, cross-bedded, upper 2 feet purplish with strong cross-bedding	17	
367. Siltstone brick red, sandy streaks, cross-bedded	2	8
366. Siltstone and sandstone interbedded, brick red; sandstone fine-grained, weathers knobby, nodules of sandstone	5	
365. Siltstone brick red, mottled with gray	11	
364. Shale and siltstone interbedded, brick red; with greenish-gray streaks, wavy bedding	2	
363. Siltstone brick red, a thin bed of sandstone containing coarse, rounded quartz grains, 4 feet above the base	12	
362. Siltstone brick red, weathers spheroidally, surface covered with small knobs 1 foot in diameter, soft between	4	
361. Siltstone brick red, mottled gray	4	
360. Sandstone and siltstone brick red, mottled with small gray spots; sandstone lenticular	2	
359. Siltstone brick red, mottled with small gray spots, calcareous	20	
358. Sandstone brick red, fine-medium-grained, weathers knobby on surface		3
357. Siltstone brick red, mottled with gray	9	
356. Shale and siltstone brick red, wavy bedding, soft		6
355. Siltstone brick red mottled with gray in festoon pattern suggesting cross-bedding	4	6
354. Shale and siltstone brick red; shale about 3 feet thick near base; siltstone lumpy, irregularly bedded	6	3
353. Siltstone brick-red, wavy bedding	6	6
352. Sandstone brick red, medium-fine-grained, knobby surface		8
351. Siltstone brick red, mottled with small gray spots	13	
350. Sandstone brick red, medium-fine-grained, arkosic, gradational contact with Int. 349		3
349. Siltstone brick red, mottled with gray	1	6
348. Sandstone, siltstone, and shale; sandstone gray, medium-fine grained, feldspathic; siltstone and shale brick red, thin, wavy bedding	1	10
347. Siltstone brick red, mottled with small gray spots	5	
346. Siltstone, shale, and sandstone interbedded; siltstone and shale brick red; sandstone pinkish gray, siltstone lenses between sandstone beds locally; 4 foot bed of shale at top	7	
345. Siltstone brick red, mottled gray in small spots	4	
344. Sandstone white, weathers soft purplish white, fine-medium-grained, feldspathic, calcareous, small sandstone nodules on weathered surface	5	2
343. Shale and siltstone interbedded; several beds of each, brick red, mottled with gray; a soft layer	2	
342. Sandstone medium-fine-grained, feldspathic, grades up into Int. 343	1	3
341. Shale and siltstone brick red, mottled gray, very wavy bedding	1	6
340. Siltstone brick red, mottled gray in small spots	4	8
339. Shale brick red, silty, soft		4
338. Siltstone brick red, mottled gray in small spots, bed of light-colored sandstone 3 inches thick near middle of interval	3	10
337. Shale and siltstone brick red, mainly siltstone except in top 6 inches, soft	1	9
336. Sandstone white, fine-grained, rounded grains of quartz, potash feldspar, calcareous; sandstone nodules on surface less calcareous than rock	1	5
335. Siltstone with thin shale breaks, brick red; 2 soft beds with hard bed between	2	10
334. Siltstone brick red, mottled gray in small spots	5	6
333. Shale and siltstone brick red, soft		5
332. Siltstone brick red, mottled with gray	9	8
331. Shale greenish gray at base, dark red above, silty, blocky fracture	1	
330. Sandstone and siltstone brick red, mottled with gray; sandstone fine-		

	Feet	Inches
medium-grained, feldspathic between 2 beds of siltstone, all calcareous	2	
329. Shale and siltstone interbedded; siltstone brick red; shale darker		10
328. Siltstone brick red, mottled with small gray spots	6	6
327. Shale and siltstone brick red and gray, wavy, striped bedding		8
326. Siltstone brick red, mottled with small gray spots	4	
325. Siltstone and shaly siltstone interbedded, brick red, mottled with small spots of grayish-white, slightly calcareous, weathers soft	3	10
324. Siltstone brick red, with a discontinuous shale bed, 1.5 feet above base	2	4
323. Shale and siltstone brick red, thin-bedded	1	
322. Siltstone brick red, mottled with greenish-white spots	4	10
321. Shale and siltstone brick red, slightly irregular bedding suggesting ripple marks, slightly calcareous, lenses of medium-grained sandstone	29	
320. Shale and siltstone similar to Int. 316		3
319. Siltstone brick red, scattered white spots	5	1
318. Shale and siltstone similar to Int. 316	1	
317. Siltstone brick red, mottled with a few white spots	5	
316. Siltstone white with a few brick-red shale partings, wavy, striped bedding	1	8
315. Siltstone brick red, slightly calcareous	1	5
314. Shale and thin-bedded siltstone, brick red	2	
313. Siltstone and sandstone; siltstone brick red with a few coarse grains of sand	2	
312. Siltstone brick red, with darker red, shiny "colloidal shale" spots on bedding planes	3	
311. Sandstone white, medium-grained, subangular to angular grains of quartz, potash feldspar; sandstone nodules in upper 6 inches	8	
Offset from steep hillside south of village of Pajarita to hillside about 1 mile west of Rowe.		
310. Siltstone brick red, thin-bedded; streaks of white siltstone at 20 feet and 32 feet above base of interval	54	
Total thickness of Yeso formation	400	5
Sangre de Cristo formation		
309. Sandstone pinkish tan, with lighter spots, fine-grained, calcareous	10	
308. Siltstone brick red, thin-bedded	22	
307. Sandstone similat to Int. 305	11	
306. Siltstone brick red, thin-bedded	3	
305. Sandstone white with red lenses, medium-coarse-grained, scattered rounded pebbles, cross-bedded (foreset beds dip E. and W.)	9	
304. Sandstone and shale; shale dark red; sandstone pinkish red, cross-bedded (foreset beds dip E.), thin-bedded	17	
303. Sandstone white and pink, medium- and coarse-grained, arkosic, conglomeratic, cross-bedded (foreset beds dip E. and W.)	38	
302. Shale and nodular limestone; shale dark red and green; limestone dark red	5	
301. Covered	5	
300. Sandstone white, medium-grained, scattered rounded pebbles of quartz and igneous rocks, up to 1 inch diameter	11	
299. Shale dark red and gray	7	
298. Limestone dark red, nodular	3	
297. Shale and sandstone; shale dark red and gray; sandstone medium-grained, thin-bedded, cross-bedded (foreset beds dip NE.)	8	
296. Sandstone white with greenish cast, medium-coarse-grained, irregular bedding, contains lenses of conglomerate some of which are red, fragments of shale and limestone up to 1 inch diameter; interval calcareous	11	
295. Partly covered; dark red shale and nodules of limestone	11	
294. Sandstone similar to Int. 290, at 7 feet above base a pinkish-red conglomeratic sandstone 3 feet thick wedges out toward west. Most of pebbles are dark red siltstone, up to 2 inches in long axis, but some are quartz and igneous rock	19	
293. Partly covered; dark red shale and nodular limestone	8	
292. Sandstone similar to Int. 290	5	
291. Covered; red shale and limestone in float	9	
290. Sandstone white, medium-grained, feldspathic, gray shale fragments	4	7
289. Shale dark red and dark green, contains some nodular limestone	3	6
288. Sandstone light gray with brownish-red streaks; medium-grained, feldspathic, cross-bedded (foreset beds dip NE.)	8	
287. Covered; probably mainly dark red shale	10	
286. Sandstone white and pale yellow, with small fragments of pale green shale, medium-grained, thin-bedded, soft	2	
285. Shale dark red	4	

	Feet	Inches
284. Siltstone similar to Int. 282	2	
283. Shale dark red	15	
282. Siltstone light gray, thin-bedded, slightly calcareous	2	
281. Shale dark red	21	
280. Limestone dark red, flecked with gray, finely crystalline	10	
279. Siltstone and shale dark red; mainly siltstone in lower half of interval, a few streaks and patches of light gray	23	
278. Siltstone light gray and brick red, becomes dark red at top; thin-bedded, slightly calcareous	4	
277. Shale dark red	11	
276. Limestone dark red	1	4
275. Siltstone dark red		6
274. Limestone dark red, finely crystalline, nodular	1	
273. Shale dark red	21	
272. Limestone similar to Int. 270	1	
271. Shale dark red	6	
270. Limestone dark brownish red, weathers gray in spots, nodular	1	
269. Shale dark red	3	
268. Limestone dark brownish red, finely crystalline, sandy	1	
267. Shale greenish gray and dark red	3	
266. Limestone gray and purple, parts weather brown, other parts dark purple, nodular, finely crystalline	1	
265. Covered; a few beds of dark red shale and gray shale and dark sandstone crop out in deep arroyo	160+	
Total thickness of Sangre de Cristo formation	513	4+

Offset to about 200 yards east of village of Pajarita about 300 yards north of U. S. Highway 85 at ledge of purplish-gray limestone.

Top of Magdalena group
Madera formation
Arkosic limestone member

Section ends on south side of Pecos River in bluff about 200 yards west of bridge north of Pecos. (Probably some strata missing between top of this section and Pajarita section.)

In arroyo east of Rowe, strata equivalent to or younger than Int. 264 contain *Triticites rhodesi*.

264. Limestone light gray, weathers gray, vertical fracture pattern	6+	
263. Covered; probably red and greenish-gray shale with thin-bedded, buff sandstone	15	
262. Sandstone yellowish brown, weathers same color but thin-bedded, medium-grained, cross-bedded, calcareous	2	
261. Covered; probably red and gray shale	7	
260. Limestone light gray, coarsely crystalline, feldspathic; granular surface makes it resemble sandpaper		9
259. Covered; probably gray shale	5	
258. Limestone medium gray, medium crystalline, thin-bedded, quartz grains weather out on surface; contains *Composita* sp. and crinoid columnals	2	
257. Sandstone and limestone interbedded; sandstone greenish gray, medium-grained; limestone similar to Int. 256	1	8
256. Limestone light gray, arenaceous, weathers with sandpaper-like surface, except for base where small fragments of pure, gray limestone rest on irregular surface of interval below		8
255. Shale and siltstone, yellowish green, very micaceous, soft; partly covered	6	6
254. Sandstone light gray, weathers yellowish gray, feldspathic, cross-bedded, medium-grained, calcareous	6	9
253. Shale and sandstone pale greenish gray, soft	8	
252. Sandstone and shale interbedded, dark red; partly covered	35	
251. Limestone medium gray, thin-bedded, with shale breaks. (Forms hogback where telephone line crosses ridge 1.5 miles west of Pecos. Contains *bryozoa*, *Neospirifer*, sp., *Composita* sp.	25	
250. Shale and siltstone greenish gray	8	
249. Shale and sandstone interbedded; shale dark red, micaceous; sandstone grayish red, several 1 foot beds; partly covered	20	
248. Sandstone buff, weathers gray-grayish red, coarse-grained, arkosic, scattered pebbles of quartz and potash feldspar, up to 1 inch diameter	10	6
247. Shale and thin sandstone beds, dark red and greenish gray; partly covered	38	
246. Limestone dark gray, weathers lighter and thin-bedded, but is massive in cliffs; a few small sand grains, a few fossils	5	6
245. Shale, sandstone, and limestone dark red-gray; sandstone fine-grained		8
244. Sandstone buff, weathers yellowish buff, coarse-grained, arkosic, calcareous, scattered pebbles of quartz	7	7
243. Shale dark red and gray; partly covered	10	
242. Sandstone light gray, weathers pinkish gray, arkosic, conglomeratic; pebbles of quartz and feldspar up to 1.5 inches in diameter; cross-bedded, bands and streaks of black sand; calcareous	4	6
241. Shale dark red	4	

	Feet	Inches
240. Limestone light gray, soft, nodular, sandy, weathers to a heap of limestone nodules	2	
239. Shale dark red; partly covered	12	
238. Sandstone greenish gray, weathers same, conglomeratic, arkosic	3	
237. Shale and limestone interbedded; shale medium gray; limestone gray, nodular, thin-bedded; 80% shale in lower half, more in upper. *Bellerophon* sp. and large discoidal flat-spired gastropods lie 26 feet above the base	45	
236. Limestone conglomerate gray, weathers buff; rounded pebbles of quartz, potash feldspar, and limestone, also coarse grains of quartz sand, fenestellid bryozoa		10
235. Limestone (70%) and shale interbedded; limestone light gray, weathers brown, finely crystalline, nodular; shale gray	3	2
234. Limestone light gray, weathers same, patches of greenish-brown chert in upper part, a few silicified fossils, chiefly *Bellerophon* sp. (This bed caps the cuesta west of monastery)	5	7
233. Siltstone gray, weathers yellowish brown, fragments of clams and productids	11	
232. Shale gray, with gray limestone nodules	8	
231. Shale dark red, and sandstone streaked dark red and pinkish gray, arkosic	85	
230. Limestone gray, ledges 2–3 feet thick above and below; middle consists of thin-bedded purplish-gray limestone containing *Triticites* cf. *T. nebraskensis*, *Neospirifer* sp., and other fossils	8	
229. Siltstone gray, weathers yellowish gray, contains *Crancrinella boonensis*, *Juresania nebraskensis*, *Dictyoclostus portlockianus*, *Marginifera* cf. *M. muricatina*, *Linoproductus* cf. *L. prattenianus*, *L.* sp., *Neospirifer* cf. *N. triplicatus*, *Composita subtilita*, *C. argentea* (?) (100% brachiopods)	5	
228. Shale and nodular limestone, gray	6	
227. Shale dark red	3	
226. Sandstone green-gray, conglomeratic, arkosic	1	
225. Covered	5	
224. Limestone medium gray, weathers lighter; lumpy, irregular beds	2	
223. Shale and nodular limestone, gray	1	
222. Shale yellowish brown, silty, slightly calcareous, thin, irregular beds; contains *Pinnatopora* sp., *Chonetina flemingi*, *Echinoconchus semipunctatus*, *Dictyoclostus portlockianus*, *D.* sp., *Neospirifer triplicatus*, *Composita subtilita*, *Pleurophorus* sp., *Myalina slocomi*, *Aviculopecten* sp., *Streblochondra* cf. *S. hertzeri*, *Euchondria* ? sp., *Acanthopecten carboniferous*, *Astartella* cf. *A. concentrica*, *Allorisma terminale*, *Edmondia gibbosa*, *Schizodus wheeleri*, *Parallelodon* cf. *P. sangamonensis*, *Naticopsis meeki*, *Donaldina robusta*, *Hemizyga tenuilirata*, *Goniasma lasallensis*, *G.* sp. (Of individuals, 2% bryozoa, 29% brachiopods, 54% pelecypods, 14% gastropods.)	23	
221. Shale gray, with thin beds of nodular, gray limestone	47	
220. Limestone and shale; partly covered; shale grey; limestone gray nodular, weathers brown	21	
219. Shale and sandstone greenish gray; sandstone medium-grained; shale micaceous	3	
218. Covered; rubble of sandstone and nodules of gray limestone	45	
217. Sandstone pink, course-grained, almost entirely potash feldspar	1	
216. Limestone light gray, weathers same, medium crystalline, irregular bedding; contains *Neospirifer* sp. and *Derbyia* sp.		
215. Covered; limestone rubble on surface	8	
214. Limestone light gray, weathers brown with sandpaper-like surface; medium crystalline; contains *Derbyia crassa*, *Juresania nebraskensis*, *Neospirifer triplicatus*, *Composita subtilita*, *C. ovata* (?)	2	6
213. Covered; float of dark red shale, greenish-gray sandstone and nodular gray limestone	58	
212. Shale and limestone; shale gray, mainly covered; limestone light gray, finely crystalline	10	
211. Limestone light gray, weathers darker, with sandpaper-like surface, medium crystalline, feldspathic; contains tabulate corals, *bryozoa*, *Composita* sp.	4	
210. Shale greenish gray and dark red with ledges of gray-green sandstone about 1 foot thick; partly covered	30	
209. Sandstone greenish gray, medium-coarse-grained, feldspathic	1	
208. Shale greenish gray and dark red, silty, micaceous; base covered	6	
207. Sandstone purplish gray, weathers same, coarse-grained, feldspathic		8
206. Shale yellowish brown, micaceous	3	
205. Covered; blocks of green sandstone in float	10	
204. Limestone light gray, weathers same, lithographic texture	2	
203. Limestone white, weathers buff, with corrugated surface; coarsely crystalline; grains of biotite, sandy		

	Feet	Inches
near top; contains *Pleurodictyum eugenae*, fenestellid *bryozoa*, *Juresania nebraskensis*, *Composita subtilita*, *C. elongata*, *Septimyalina perattenuata*, *Myalina cuneiformis*, *Pleurophorus* sp. (Of individuals, 10% corals, 24% bryozoa, 36% brachiopods, 30% pelecypods.)	13	
202. Limestone nodules yellow greenish gray, in soft, gray shale matrix; limestone very coarsely crystalline, hard; fossil fragments	1	
201. Sandstone and shale interbedded; shale yellowish green, weathers pinkish gray, medium-coarse-grained, arkosic; shale green, micaceous	13	
200. Shale gray-green and dark red, probably some sandstone ledges; partly covered	36	
199. Sandstone brownish green, weathers same, medium-coarse-grained, cross-bedded, feldspathic, calcareous	15	
198. Sandstone pale green, weathers brownish green, medium-coarse-grained, arkosic, soft, perhaps shale breaks between sandstone beds	24	
197. Limestone and shale; shale gray, micaceous; limestone gray, nodular; contains *Composita* sp	7	
196. Limestone light gray, weathers brownish gray with sandpaper-like surface; medium cyrstalline, arenaceous; thin gray shale beneath	1	
195. Sandstone greenish gray, weathers tan, coarse-medium-grained, arkosic; conglomeratic at top, pebbles of pegmatite, and metamorphic rocks up to 3 inches diameter, calcareous	3	
194. Shale green and dark red; at least 3 beds of medium-fine-grained green sandstone near middle of interval, each 6 inches thick	21	
193. Conglomerate and sandstone; sandstone matrix greenish gray, weathers maroon; coarse-grained, calcareous; fragments of schist, quartzite, epidote, quartz, potash feldspar up to 6 inches diameter	3	
192. Shale greenish, silty	2	
191. Sandstone pale green, weathers green; a few red spots, coarse-grained, arkosic	1	
190. Mainly covered; shale brownish green and dark red, with green sandstone	13	
189. Sandstone pale green, feldspathic, fine-grained below, coarse-grained above	2	
188. Shale brown and red with outcrop covered with rubble of purplish-gray limestone nodules	14	
187. Sandstone pinkish gray, weathers tan; arkosic, conglomeratic, rounded fragments of quartz, acid igneous and metamorphic rocks, potash feldspar up to 2 inches in diameter	3	
186. Covered; probably shale with nodules of gray limestone at top	12	
185. Shale yellow brown, silty	6	
184. Mainly covered; ledges of green and buff sandstone, conglomeratic	32	
183. Sandstone similar to Int. 175, but contains *Spirifer rockymontanus*, *Composita elongata*, *C.* sp., *Euconospira* sp., *Straparollus* sp. (Of individuals, 72% brachiopods, 28% gastropods.)	26	
182. Shale and limestone; shale weathers brown, silty; limestone gray, nodular	10	
181. Limestone gray, weather brownish-gray, very sandy, many small crinoid columnals	5	
180. Covered	5	
179. Sandstone pale green, weathers brownish green, micaceous, some beds fine-grained, others conglomeratic, fragments of acid igneous, and metamorphic rocks up to 2 inches in diameter; feldspathic	11	
178. Shale brownish green and red, perhaps a thin red limestone near base	20	
177. Limestone light gray, weathers same, nodular, and shaley near base; upper part similar to Int. 178	8	
176. Limestone light gray, weathers lighter, medium crystalline, scattered quartz grains	4	
175. Sandstone light gray, weathers pale greenish gray, coarse-grained, very calcareous, arkosic; contains *Spirifer rockymontanus*, *Composita* several types, perhaps all are variations of *C. subtilita*	10	
174. Sandstone gray weathers greenish gray; medium-grained, feldspathic, thin-bedded, cross-bedded, thin limy beds near top	31	
173. Conglomerate pale gray, weathers buff; matrix coarse-grained sandstone; angular fragments small, light and dark quartz, potash feldspar; calcareous; a few *Composita*	23	
172. Sandstone gray, weathers brown, fine-grained, calcareous	10	6
171. Covered; perhaps gray and brown shale	10	
170. Conglomerate dark green; matrix sandstone, coarse-grained; fragments of quartz, potash feldspar up to 2 inches in diameter	1	
169. Covered	15	

	Feet	Inches
168. Sandstone pale green, weathers pinkish-gray in blocks, coarse-grained, conglomeratic	30	
167. Sandstone pale green below, dark green above, very calcareous, upper part weathers into arenaceous "sponge rock", top conglomeratic	2	
166. Covered; probably brown shale	5	
165. Covered; float of large blocks of green sandstone, weather pinkish-red	47	
164. Limestone light gray, weathers darker; very coarsely crystalline, sandy; contains a few corals and many fenestellid bryozoans	3	
163. Covered; gray-brown shale and limestone rubble	20	
162. Sandstone buff, weathers yellow and red; conglomeratic, coarse-grained	5	
161. Limestone medium gray, weathers yellowish brown; medium crystalline, flinty, contains many *Derbyia* sp. and *Dictyoclostus* sp.	15	
160. Covered; shale and thin sandstone in float	5	6
159. Limestone medium gray, weathers brownish gray, medium crystalline, contains a few small crinoid columnals, *Composita* sp.; thin, coarse-grained sandstone at base	5	
158. Shale yellowish brown below, dark red above	10	
157. Sandstone pale green, weathers greenish brown; coarse-grained, conglomeratic, pebbles of quartz up to 1 inch in diameter	4	
156. Shale yellowish brown and red with a thin bed of sandstone near middle of interval	16	
155. Sandstone pale green, weathers same; medium-coarse-grained	11	
154. Covered	15	
153. Limestone gray	2	
152. Covered; scattered blocks of limestone and sandstone in float	32	
151. Sandstone weathers yellow, cavernous, medium-fine-grained	25	

Offset on Int. 150 south to west side of a dry valley which is tributary to Pecos River, about .25 mile west of Pecos River road at Romolla ranch, which is about 1.5 miles north of Fish Hatchery.

Total thickness of Arkosic limestone member	1375	9+

Gray limestone member

150. Limestone light gray, some beds white porcelanous, blocky fracture, thin-bedded, nodule-like spots weather differentially on surface; 7th prominent limestone cliff	24	
149. Limestone light gray with dark spots, thin-bedded, paper-thin shale beds between limestone beds	5	6
148. Limestone very light gray, coarsely crystalline, thick-bedded, seems to show cross-bedding or unconformity in middle of interval	5	
147. Shale gray, nodular	1	
146. Sandstone olive green, weathers yellowish green, fine-grained		11
145. Shale red and green	4	
144. Sandstone green, medium-to coarse-grained, arkosic	2	
143. Covered	5	
142. Limestone light gray, weathers darker gray, greenish spots and bands; lumpy bedding near top	3	2
141. Covered	2	
140. Limestone light gray, weathers medium gray with yellow bands and spots	1	
139. Covered; talus slope	2	
138. Limestone and shale interbedded; light gray, weathers darker, dark flinty spots in limestone; contains fusulinids	4	3
137. Covered; perhaps shale	8	
136. Limestone light gray, pinkish cast in some beds, fossiliferous, massive bed below, thinner bedded above	3	
135. Limestone very pale gray, oölitic, weathers with uneven surface; contains *Fusulina* cf. *F. socorroensis*	3	7
134. Covered; probably a green sandstone and a red and green shale near base	28	
133. Limestone medium gray, weathers brownish gray, irregular bedding resulting from paper-thin shale layers	5	
132. Shale very light gray, soft; base covered	1	
131. Limestone light gray, weathers brownish gray, coarse grains of quartz and potash feldspar which weather out on surface	5	
130. Covered	4	11
129. Shale dark red and green	2	
128. Sandstone green, fine- to coarse-grained	1	
127. Limestone light gray, weathers same, relatively even bedding, upper beds have light spots of medium gray limestone in lighter matrix; contains *Fusulina novamexicana* at top; 6th prominent limestone cliff	13	
126. Limestone and shale interbedded, dark gray, irregular bedding, few fossils	8	5
125. Covered with talus; probably some dark shale; float blocks contain *Astartella* sp. and large fusulinids	16	6
124. Sandstone pale olive green, weathers darker gray, coarse-fine-grained, arkosic, conglomeratic	3	

	Feet	Inches
123. Limestone light gray weathers lighter gray, irregular bedding, with paper-thin shale layers between beds; 5th prominent limestone cliff	30	
122. Limestone (60%) and shale interbedded, light gray	15	
121. Sandstone pale olive green, fine-grained	1	
120. Limestone light gray, weathers yellowish-gray; thin-bedded, argillaceous, contains coral and crinoid fragments, *Wedekindellina excentrica*	1	4
119. Limestone dark gray, weathers light gray to brownish gray, finely crystalline, irregularly bedded, a few fossils	5	6
118. Limestone and shale medium gray, weathers light brown; limestone nearly lithographic, beds up to 8 inches thick; contains *Wedekindellina excentrica*	9	6
117. Covered	22	
116. Sandstone pale bluish green, medium- to fine-grained, arkosic, a few angular pebbles of quartz up to 2 inches kn diameter	3	
115. Covered	1	5
114. Limestone light gray, weathers brownish gray in spots, each spot surrounded by yellow	2	
113. Sandstone olive green, weathers greenish brown, beds range from coarse- to fine-grained, contains impressions of clams in fine-grained beds	6	
112. Limestone dark gray, crystalline, lumpy bedding, beds apparently separated by paper-thin shale layers; contains *Fusulina* sp. (large), fenestellid bryozoans, *Derbyia crassa*, *Composita subtilita*, *Edmondia gibbosa*, trilobite fragment	2	4
111. Limestone light gray, ledges 1 foot thick	3	
110. Limestone and shale interbedded, light gray, fossiliferous, beds 8 inches to 1 foot thick	14	
109. Limestone dark gray, weathers brown gray, finely crystalline, large crinoid columnals and other fossils	1	10
108. Limestone light gray, weathers gray brown, fragments of quartz imbedded in limestone matrix	8	
107. Conglomerate white, weathers yellow, subangular pebbles up to 3 inches in diameter; light and dark quartz sand matrix, fine-grained, calcareous; contact with Int. 108 has about 1 foot of relief	6–7	
106. Limestone (80%) and shale interbedded, light gray; coquina of *Dictyoclostus* sp. and a few other gener lies between 25 and 35 feet above base; 4th prominent limestone cliff	62	
105. Limestone (60%) and shale interbedded, dark gray, weathers brownish gray, very fossiliferous, fossils resemble those in Int. 93	12	
104. Covered; probably shale	6	
103. Sandstone pale olive green, fine-grained with scattered large pebbles of quartz		6
102. Sandstone buff, weathers yellow buff, conglomeratic, rounded and subangular pebbles of quartz, up to 1.5 inches in diameter		10
101. Limestone light gray, weathers yellow brown, thin shale beds between lumpy beds of limestone, a few fossils	4	3
100. Limestone light gray, weathers yellow brown, thin beds of shale		8
99. Limestone (70%) and shale interbedded; limestone dark gray, weathers yellow gray; shale thin, yellow brown; contains *Marginifera* sp., *Chonetina* sp., *Composita* sp.	6	3
98. Covered; probably mainly gray shale	3	
97. Limestone yellow brown, argillaceous, sandy; contains *Marginifera* sp., *Spirifer* sp.	1	
96. Limestone light gray, one bed	1	8
95. Limestone light gray, weathers yellow brown, irregular bed, argillaceous, forms rough surface in cliff; contains *Wedekindellina excentrica*, *Fusulina novamexicana*, *Marginifera* sp.	11	
94. Limestone (70%) and shale interbedded, light gray, finely crystalline, hard, nodular; most of shale at top; very fossiliferous	11	9
93. Shale dark gray, with thin nodular limestone; shale slightly calcareous, contains bryozoans (10%), *Juresania nebraskensis* (7%), *Mesolobus mesolobus* (21%), *Marginifera haydenensis* (22%), *M. ingrata* (3%), *M.* sp. (7%), *Phricodothyris perplexa* (3%), *Spirifer opimus* (14%), *Neospirifer triplicatus* (7%), *Composita* (?) sp. (3%), *Pernopecten attenuatus* (3%)	5	4
92. Limestone gray green, weathers green brown, many medium and coarse grains of quartz; fossiliferous	11	
91. Shale and sandstone interbedded, similar to Int. 89 and 90	2	
90. Sandstone olive green, medium-grained, a few grains of pink quartz, noncalcareous		8
89. Shale olive green	1	
88. Limestone brownish gray, sandy		7

	Feet	Inches
87. Shale and limestone interbedded, dark gray; shale slightly micaceous, calcareous; limestone nodular; interval fossiliferous	1	1
86. Shale yellow brown with gray streaks, sandy, raised marks like those on cake-icing on surface of bedding planes		10
85. Limestone yellow brown, weathers same, upper 1 inch sandy; fossiliferous		8
84. Limestone similar to Int. 83, but buff with small lumps of dark gray limestone, beds up to 6 inches thick	12	
83. Limestone light gray, weathers bluish gray, with tan beds; thin irregular beds separated by paper-thin shale beds	4	6
82. Limestone conglomerate; matrix dark gray limestone; angular and subangular pebbles of quartz up to 1 inch in diameter		4
81. Sandstone light gray, weathers tan; medium-grained, thin-bedded, some beds calcareous	1	
80. Limestone light gray, weathers tan, oölitic, sandy		11
79. Shale yellow brown, micaceous	1	
78. Limestone dark gray, weathers light gray; nodular bedding, thin shale breaks; silicified *Lophophyllidium* sp	1	5
77. Limestone dark gray, massive, very fossiliferous	2	8
76. Shale light gray, nodular	3	9
75. Limestone (40%) and shale interbedded, dark gray, weathers brown, contains crinoid columnals, bryozoans, productids, *Neospirifer* sp	5	4
74. Limestone dark gray, weathers brownish gray; very fossiliferous, grades up into Int. 74	3	
73. Covered; perhaps shale	1	
72. Limestone light gray, weathers yellowish gray; finely crystalline, thin irregular beds; slightly softer at base; contains *Phricodothyris perplexa* (50%), *Neospirifer goreii* (8%), *Composita subtilita* (?) (33%), *C.* (?) sp. (8%), crinoid columnals	7	
71. Limestone light gray, weathers same; massive, top layer contains dark red silicified cup corals; 3rd prominent limestone cliff	12	1
70. Shale gray with thin beds of limestone; partly covered	5	
69. Limestone gray, weathers yellow brown	4	6
68. Limestone and shale interbedded, black, weathers yellow brown; fossiliferous	2	5
67. Limestone gray, weathers yellow gray; irregular beds with thin breaks of shale (about 20% shale)	4	9
Total thickness of Gray limestone member	555	6
Sandia formation		
Clastic member		
66. Shale gray		8
65. Coal, bituminous, impure, with plant remains		6
64. Limestone dark gray, weathers brownish gray; irregular bedding		4
63. Shale light and dark gray	4	
62. Limestone light gray, weathers greenish gray, many fossils		6
61. Shale dark gray, fissile, calcareous; contains bryozoans, *Orbiculoidea capuliformis* (25%), *Mesolobus mesolobus* (13%), *Neospirifer triplicatus* (12%), *Composita subtilita* (50%)		9
60. Limestone gray, weathers brownish gray; lumpy bedding, many productids, *Neospirifer* sp	3	6
59. Limestone and shale interbedded (60%) shale); limestone dark gray; shale very dark gray, hard, calcareous	7	
58. Sandstone tan, conglomeratic, quartzitic	3	
Offset one eighth mile north along hillside to deep arroyo.		
57. Partly covered; ledges of gray limestone	10	8
56. Limestone light gray, weathers brownish gray; sugary surface, many poorly preserved small *Linoproductus* sp	1	1
55. Shale greenish gray; partly covered	1	7
54. Limestone yellow, weathers yellow brown with a pitted surface, few fossils	1	5
53. Limestone black, similar to Int. 51, but contains *Fusulinella famula.*	2	
52. Covered	2	6
51. Limestone black, weathers brownish gray; thin-bedded, contains *Derbyia crassa* (16%), *Juresania nebraskensis* (3%), *Dictyoclostus* sp. (3%), *Marginifera* cf. *M. scintillata* (10%), *M. ingrata* (10%), *M. missouriensis* (3%), *Linoproductus* sp. (3%), *Cryptocantha whitei* (2%), *Spirifer rockymontanus* (2%), *Neospirifer goreii* (2%), *N. cameratus* (13%), *Composita subtilita* (31%), *Myalina cuneiformis* (2%)	2	
50. Covered; possibly shale	3	
49. Limestone grading downward into shale; limestone medium gray,		

	Feet	Inches
weathers lighter; irregularly bedded, contains *Composita* sp. and other fossils	2	5
48. Covered; possibly shale	4	
47. Sandstone yellow-brown, weathers same, coarse-grained	5	
46. Limestone gray, weathers yellowish buff, blocky fracture; 2nd prominent limestone cliff	17	6
45. Covered	20	
44. Limestone light gray, weathers darker; medium crystalline, contains *Dictyoclostus* sp. and other fossils near top	4	1
43. Covered; probably limestone and shale	11	
42. Limestone gray, with orange spots, weathers yellow brown to buff; irregular bedding, fossiliferous	1	
41. Covered	25	
Offset 200 feet north		
40. Sandstone, limestone, and shale in alternating beds; sandstone irregularly bedded; shale thin, forms series of irregular ledges on slope; yields much float	21	
39. Limestone dark gray, with black spots, weathers yellow brown; impure, dolomitic ?, irregular bedding, contains *Dictyoclostus* sp., *Marginifera ingrata*, *Spirifer occidentalis*		10
38. Covered; numerous prospect pits to south suggest that a thin coal seam in this interval	51	
37. Sandstone light gray and dark green, weathers brown and green, nodules of brown and gray calcite; gray nodules may be algal	1	2
36. Shale, weathers yellow brown	13	
35. Limestone light gray, weathers darker; scattered grains of quartz up to 3 mm. diameter	1	9
34. Sandstone grades laterally into limestone within a few inches; sandstone dark yellow, noncalcareous; limestone gray with a thin shale break at top	1	7
33. Shale similar to Int. 29	14	
32. Sandstone olive green, weathers dark brown, limonitic stains; one bed	1	11
31. Shale similar to Int. 29	8	
30. Quartzite black, with large fragments of white and blue quartz	1	1
29. Shale weathers yellow brown; partly covered	10	
28. Limestone and shale interbedded; limestone light gray, weathers brownish gray, thin-bedded, argillaceous; shale yellowish brown; contains *Schizophoria* sp., *Meekella* sp., *Composita* sp., and other fossils	2	
27. Covered; probably shale	28	
26. Shale gray, weathers yellowish brown	11	
25. Siltstone similar to Int. 23	3	
Offset one quarter mile south along hillside.		
24. Shale light gray at base, medium gray above; minute spheres in upper part	6	
23. Siltstone olive green, weathers yellow green, thin-bedded; blocky fracture	6	
22. Shale weathers olive green; nodules of red chalcedony; interval becomes limy toward south	2	10
Total thickness of Clastic member	207	3
Total thickness of Pennsylvanian and Permian	3473	11
Sandia formation		
Limestone member		
21. Limestone greenish gray, weathers dark brown; finely crystalline, thin beds stand out in relief; contains limestone pebbles farther south	3	4
20. Limestone light greenish gray, weathers medium gray; irregular bedding	2	2
19. Limestone light gray, weathers darker, stylolitic, irregular contact with Int. 20	7	6
18. Covered; probably yellowish-brown shale	3	
17. Limestone medium gray, finely crystalline; contains a few fragments of brown chert	6	
16. Siltstone buff, weathers gray; a few grains of sand; very calcareous	10	6
15. Limestone lighter gray than Int. 14; lumpy bedding, lumps harder and more flinty toward top; 1.6 feet below top is a 1 inch bed of conglomerate composed of angular fragments of red chert up to 1 inch in diameter; 1st prominent limestone cliff	37	
14. Limestone dark gray, weathers brownish gray, finely to coarsely crystalline, weathers blocky	17	3
Small fault in arroyo		
13. Sandstone yellow brown, weathers same; argillaceous, limy, medium-grained, grains rounded, some shale bands near top	1	3
12. Covered; probably shale	1	6
11. Limestone with thin shale beds; limestone light gray, weathers darker, scattered grains of quartz; beds up to 8 inches thick; shale gray, thin-bedded	3	4
10. Sandstone yellowish gray, weathers yellowish brown; calcareous, scattered coarse grains of quartz	1	2
9. Limestone medium gray, weathers darker; crystalline, small lumps of		

	Feet	Inches
limonite, scattered grains of quartz in lower 6 inches	2	
8. Shale gray, thin-bedded, limy beds		8
7. Sandstone white to buff, calcareous, large grains of quartz in a finer matrix		2
6. Limestone light gray, argillaceous, thin shale breaks, becomes more shaly toward top of interval	1	11
5. Shale gray with limestone nodules, scattered rounded grains of quartz	2	2
4. Limestone light gray, weathers tan; finely crystalline; subangular grains of quartz weather out in relief		10
3. Sandstone with shale breaks; sandstone buff, fine-grained with coarse fragments in it; shale light gray, paper-thin	1	4
2. Sandstone tan, weathers yellow; medium-coarse-grained, scattered pebbles of quartz, cross-bedded (foreset beds dip N., NW.), beds 6–8 inches thick	2	5
1. Conglomerate tan, rounded pebbles of quartz in sandstone matrix; grades upward into cross-bedded sandstone	1	

Rests nonconformably on Precambrian hornblende gneiss and schist. Section begins on west side of Pecos River about a quarter mile west of bridge over river at Dalton Creek Picnic Ground, 5 miles north of Pecos, San Miguel County, New Mexico.

Whiskey Creek Pass Section

Section of the late Paleozoic strate between Whiskey Creek Pass, Costilla County, and Monument Lake, Las Animas County, Colorado.

Section ends on hill top just south of Monument Lake resort at contact of Sangre de Cristo formation and Entrada sandstone.

Top of section

Interval		Feet
Sangre de Cristo formation		
421. Covered here. On east side of lake consists mainly of sandstone, grayish-red*, streaked with greenish gray, medium-grained, conglomeratic		316
420. Sandstone grayish red, mottled with pale green, coarse-grained		69
419. Covered		86
418. Sandstone grayish red, medium-grained		2
417. Covered; probably red siltstone, and grayish-red sandstone		43
416. Sandstone grayish red, medium-grained, scattered pebbles		4
415. Covered; probably red siltstone		26
414. Sandstone grayish red, mottled with pale green, medium-grained, scattered pebbles		20
413. Covered; probably red siltstone		45
412. Sandstone grayish red, mottled with pale green, medium-grained, scattered pebbles		11
411. Covered; probably red siltstone		64
410. Sandstone grayish red, medium-grained, scattered pebbles; forms cliff		3
409. Covered; red sandstone and siltstone in float		156
408. Sandstone pale red (10 R 6/2), weathers same, coarse-grained, arkosic		8
407. Sandstone (50%) and siltstone; sandstone grayish red, medium-grained, three beds; siltstone lighter than dark reddish brown, three beds; several small dikes near top of interval		78
Cross highway at a point between bridge over Whiskey Creek and entrance to Monument Lake resort.		
406. Covered		190
405. Siltstone lighter than dark reddish brown		6
404. Sandstone grayish red (5 R 4/2), medium-grained, thin-bedded		5
403. Covered		20
402. Sandstone and siltstone similar to Int. 398		24
401. Sandstone and conglomerate (20%), grayish red (5 R 4/2) some spots of light greenish gray (5 GY 8/1); sandstone coarse-grained, arkosic, cross-bedded, conglomerate mainly at base of interval, rounded fragments of metamorphic rocks up to 6 inches in diameter		13
400. Sandstone and siltstone similar to Int. 398		42
399. Covered		28
398. Sandstone (50%) and siltstone; sandstone grayish red, medium-grained; siltstone dark reddish brown, resembles Yeso formation		40
397. Sandstone and conglomerate similar to Int. 393–394. Beds of conglomerate at top and bottom grade vertically into coarse-grained sandstone, fragments of gneiss and schist up to 6 inches in diameter; 2 feet of sandstone dark reddish brown, fine-grained in middle of interval		25
396. Siltstone and sandstone lighter than dark reddish brown; sandstone fine-grained; limestone nodules, greenish gray, near middle of interval		34
395. Sandstone grayish red (5 R 4/2) streaked with pale green, weathers very pale orange, medium-and coarse-grained, scattered pebbles		9
394. Conglomerate grayish red (5 R 4/2) streaked with pale green; matrix coarse-grained sandstone; rounded fragments		

*Names of colors are those listed in the *Rock Color Chart*, National Research Council, 1948.

	Feet
of metamorphic rocks and quartz up to 3 inches in diameter; grades up into Int. 395	4
393. Sandstone and siltstone interbedded; sandstone grayish red (5 R 4/2), coarse-grained, scattered pebbles; siltstone dark reddish-brown, with a few limestone nodules	32
392. Covered; small arroyo	48
391. Conglomerate grayish red (5 R 4/2), weathers same; matrix coarse-grained, arkosic sandstone; subangular and rounded fragments of metamorphic rocks up to 4 inches in diameter; upper 10 feet, partly covered	44
390. Covered	36
389. Sandstone pale red (5 R 6/2) mottled with pale green, coarse-grained, scattered pebbles of quartz up to .5 inch in diameter	12
388. Covered; small arroyo	84
387. Sandstone and siltstone in alternating beds; sandstone grayish red (5 R 4/2) and dark reddish brown, scattered pebbles, mainly in base of interval; siltstone lighter than dark reddish brown; resembles alternating Abo and Yeso lithology	195
386. Siltstone dark reddish brown with limestone nodules	3
385. Sandstone pale red (5 R 6/2), weathers darker, medium-grained, arkosic, scattered pebbles of feldspar and metamorphic rocks. (Fence crosses irrigation ditch here.)	27
384. Sandstone grayish red (5 R 4/2) mottled with pale green, medium-coarse-grained	9
383. Siltstone (90%) and sandstone; siltstone dark reddish brown, thin-bedded, with two beds of limestone nodules; sandstone same color, fine-grained	18
382. Sandstone lighter than grayish red (5 R 4/2), streaks of pale green, massive; 3 feet of siltstone dark reddish brown, thin-bedded, 3 feet below top of interval	23
381. Sandstone grayish red (10 R 4/2), fine-grained, arkosic, calcareous	36
380. Covered	60
379. Sandstone (70%) and siltstone interbedded; grayish red (10 R 4/2) and dark reddish brown; sandstone fine- and medium-grained, basal bed has purplish cast; siltstone dark reddish brown, micaceous, with 2 beds of limestone nodules	93
378. Hornfels olive gray (5 Y 4/1)	13
Basaltic porphyry sill, 21 feet thick.	
377. Sandstone dusky yellow, arkosic, baked, conglomeratic, scattered fragments of metamorphic rocks up to 3 inches in diameter	6
376. Sandstone (50%) and siltstone grayish red (5 R 4/2); sandstone fine-grained	18
375. Sandstone grayish red (10 R 4/2), medium- and coarse-grained, conglomeratic, subangular and rounded fragments of metamorphic and igneous rocks up to 2 inches in diameter	15
374. Covered	9
373. Siltstone lighter than dark reddish brown, with nodular limestone; igneous dike in this interval	14
372. Sandstone similar to Int. 370, but with less conglomerate	8
371. Sandstone (70%) and siltstone interbedded; sandstone grayish red (5 R 4/2), weathers darker; siltstone dark reddish-brown. (Fence crosses irrigation ditch here.)	34
370. Sandstone (60%) and conglomerate grayish red (5 R 4/2), mottled pale green; sandstone coarse-grained, arkosic, irregular bedding; conglomerate, rounded fragments of metamorphic rocks up to 3 inches in diameter	20
369. Sandstone (70%) and siltstone interbedded, dark reddish brown, except at base where baked; sandstone fine-grained	15
Basalt porphyry sill, 7 feet thick.	
368. Sandstone grayish red (10 R 4/2), baked, fine-grained	1
367. Covered; 2 feet of sandstone grayish red, 6 feet below top	43
366. Sandstone pale red (5 R 6/2), medium- and coarse-grained, conglomeratic at base, rounded fragments of igneous and metamorphic rocks up to 6 inches in diameter, irregular contact with Int. 365	5
365. Sandstone and siltstone interbedded; sandstone pale red (5 R 6/2); siltstone dark reddish brown, with three beds of limestone nodules	47
364. Covered	13
363. Sandstone similar to Int. 357, but with beds of dark reddish-brown siltstone bearing limestone nodules	24
362. Siltstone dark reddish brown, limestone nodules	6
361. Sandstone similar to Int. 357	10
360. Siltstone dark reddish brown, small limestone nodules; 2 feet of sandstone, same color, in middle of interval	8
359. Sandstone similar to Int. 357	22
358. Siltstone and sandstone dark reddish brown; sandstone fine-grained; siltstone bears many limestone lumps and nodules in upper 10 feet	25
357. Sandstone pale red, some beds dark reddish brown, former conglomeratic, with rounded fragments of igneous rocks up to 2 inches in diameter, cross-bedded, medium-grained, irregular contact with Int. 356	35
356. Siltstone dark reddish brown; pale red limestone nodules near base	6

	Feet
355. Sandstone pale red (5 R 6/2) mottled with pale green, cross-bedded, small lenses of conglomerate with pebbles up to 1 inch in diameter	31
354. Siltstone dark reddish brown, weathers hackly; micaceous; pale red limestone nodules and lumps	7
353. Sandstone pale red (10 R 6/2) and light gray, a silvery sheen because of much mica; medium-grained, cross-bedded	13
352. Sandstone (70%) and siltstone; medium-grained sandstone, grayish red; fine-grained, dark reddish brown; siltstone dark reddish brown, some beds of nodular limestone	87
Leave road and follow irrigation ditch.	
351. Sandstone and siltstone dark reddish brown; siltstone has nodular limestone beds	6
350. Sandstone dark reddish brown, fine-grained	5
349. Siltstone lighter than dark reddish brown, sandy near base; contains limestone nodules, pale red, weather moderate yellowish brown	9
348. Sandstone grayish red (10 R 4/2) and pale red (6 R 6/2), medium-grained, scattered pebbles	26
347. Sandstone (70%) and siltstone; pale red sandstone, conglomeratic; dark reddish brown, fine- and medium-grained; siltstone dark reddish brown; 7 beds of nodular limestone, one at top of interval	131
346. Conglomerate pale red (5 R 6/2); sandstone matrix, coarse-grained, arkosic, rounded fragments of quartz, acid igneous, and metamorphic rock, up to 2 inches in diameter	3.5
345. Sandstone and siltstone interbedded; sandstone mainly pale red (5 R 6/2); siltstone dark reddish gray	10
344. Siltstone and sandstone dark reddish brown; sandstone fine-grained; bed of limestone nodules at top	7
343. Sandstone pale red (5 R 6/2), medium grained, and dark reddish brown, fine-grained; slightly conglomeratic at top	20
342. Siltstone dark reddish brown, with pale red limestone nodules	3
341. Covered	5
340. Sandstone dark reddish brown, fine-grained, a few medium-grained beds	6
339. Sandstone (50%) and conglomerate light gray and grayish orange pink; sandstone coarse-grained; conglomerate, subangular and round fragments of metamorphic, acid igneous rocks, and quartz up to 2 inches in diameter	9.5
338. Siltstone dark reddish brown, with limestone nodules, pale reddish brown	2.5
337. Covered	5
336. Sandstone pale red (10 R 6/2), coarse-grained, conglomeratic, cross-bedded; a few beds dark reddish brown, fine-grained, soft	10
335. Siltstone or fine-grained sandstone dark reddish brown, a few limestone nodules; weathers soft	5
334. Sandstone pale red (5 R 6/2), mottled pale green, fine-medium-grained; a few beds of finer-grained, dark reddish-brown sandstone	9.5
333. Siltstone dark reddish brown, micaceous, with nodules of limestone, pale reddish brown; weathers moderate yellowish brown; irregular contact with Int. 334	11
332. Sandstone similar to Int. 330, conglomeratic	10
331. Sandstone dark reddish brown and pale red (10 R 6/2), former fine-grained, latter medium-grained	8.5
330. Sandstone (60%) and conglomerate darker than pale red (10 R 6/2); sandstone medium- and coarse-grained, cross-bedded (foreset beds dip NW.); conglomerate with fragments of igneous, and metamorphic rocks up to 3 inches in diameter	18
329. Sandstone dark reddish brown, weathers soft, hackly fracture; lumps and nodules of grayish-red (10 R 4/2) limestone, weather moderate yellowish brown	2
328. Sandstone dark reddish brown and grayish red (10 R 4/2), mottled with pale green, fine- and medium-grained, massive	7.5
327. Sandstone and siltstone dark reddish-brown; sandstone fine-grained; siltstone has nodules of grayish-red (10 R 4/2) limestone, most of which are in top 1 foot of interval	5.5
326. Sandstone grayish red (5 R 4/2), fine- and medium-grained, massive, arkosic; upper 10 feet pale brown, conglomeratic with fragments of igneous rock up to .5 inch diameter	26
325. Sandstone dark reddish brown, fine-grained, thin-bedded; worm trails	4
324. Siltstone lighter than dark reddish brown, with nodules of pale brown limestone	3.5
323. Sandstone pale brown, coarse-grained, conglomeratic, irregular contact with Int. 322	12
322. Siltstone dark reddish brown, with nodules of pale brown limestone	2.5
321. Sandstone pale brown and grayish red, striped with pale green, fine-grained; lumps of dark red siltstone near middle of interval weather cavernous, a few beds of siltstone near top of interval	43
320. Sandstone (50%), siltstone (40%), and shale dark reddish brown, sandstone fine-grained, micaceous; siltstone and shale weather soft with hackly fracture.	13

	Feet
319. Sandstone pale brown, medium-grained, conglomeratic at base, irregular contact with Int. 318	8.3
318. Sandstone (70%) and siltstone; sandstone dark reddish brown and pale brown depending on grain size, mainly fine-grained; siltstone dark reddish brown	8.5
317. Covered (70%); siltstone and sandstone dark reddish brown, fine-grained	10
316. Sandstone similar to Int. 314	20
315. Siltstone dark reddish brown, micaceous; nodules of pale brown limestone	3
314. Sandstone pale brown, medium-coarse-grained, cross-bedded, conglomeratic; a few lenses of siltstone, dark reddish brown	24
313. Sandstone (70%) and siltstone; sandstone pale brown mottled pale green, fine-medium-grained; siltstone dark reddish brown, soft	5.4
312. Siltstone (50%) and sandstone dark reddish brown, scattered nodules of pale brown limestone, weather soft, with hackly fracture	13
311. Sandstone pale brown, mottled with pale green, slightly conglomeratic	7
310. Sandstone dark reddish brown, upper part fine-grained, lower part medium-grained, weathers with hackly fracture; nodules of pale brown limestone at top of interval	2.5
309. Sandstone pale brown, medium-grained, lenses of pebbles of quartz, igneous and metamorphic rocks up to 3 inches in diameter, irregular contact with Int. 308; makes prominent cliff	26.5
308. Siltstone (60%) and sandstone dark reddish brown, a few streaks of pale green; a 1-foot bed of pale brown nodular limestone, 3 feet above base of interval	18
307. Sandstone similar to Int. 305	5.4
306. Sandstone dark reddish brown, fine-grained, with lenses of pale red; medium-grained, massive, weathers with hackly fracture, grades up into Int. 307	9.5
305. Sandstone mainly pale red (10 R 6/2), medium-grained, a few lenses of conglomerate with pebbles of quartz, and feldspar up to .5 inch in diameter; cross-bedded, grades up into Int. 306	7.5
304. Siltstone similar to Int. 302	5
303. Siltstone dark reddish brown, more sandy near top; quartz fragments and limestone nodules; slightly calcareous, massive, weathers with hackly fracture	7.5
302. Siltstone similar to Int. 300, but with irregular spots of pale green	2.8
301. Sandstone pale red (5 R 6/2), weathers darker; medium-grained, lumps of dark reddish brown siltstone	17.5
300. Siltstone (or perhaps sandstone), dark reddish brown, nodules of limestone light brownish gray (5 YR 6/1), up to 3 inches in diameter	3
299. Siltstone (50%) and sandstone interbedded; siltstone dark reddish brown; sandstone pale red (10 R 6/2), fine-grained; grades up into Int. 300	5
298. Sandstone greenish gray (5 GY 6/1) medium- and coarse-grained, conglomeratic, rounded fragments of acid igneous rocks up to 3 inches in diameter	6.5
297. Sandstone dark reddish brown, one band of light gray; fine-grained, soft	4.5
296. Sandstone light brown ranging to dark reddish brown, the lighter colored beds, coarse-grained, conglomeratic with subangular fragments of quartz and feldspar up to 4 inches in diameter; darker layers lumpy, nodular	15
295. Sandstone (60%) and siltstone interbedded, dark reddish brown; sandstone slightly lighter color, fine-grained; siltstone weathers soft with hackly fracture	12.5
Offset to unimproved road along Whiskey Creek about .25 mile west of point where highway crosses creek. Section begins on east side of vertical fault and continues down stream.	
294. Measured on north bank of North Fork of Purgatoire River. Mainly covered. Thirty beds of sandstone, and conglomerate dark reddish brown and pale red, beds range between 3 and 15 feet thick, alternating with covered intervals which are probably underlain by finer-grained strata; sandstone coarse- and medium-grained, feldspathic; conglomerate mainly in lower 500 feet, with fragments of quartz, igneous, and metamorphic rocks up to 5 inches in diameter. Perhaps some bedding faults in this part of section	3000±
Fault, west side upthrown	
293. Sandstone pale red (10 R 6/2) medium-coarse-grained, cross-bedded, massive, cliff-former. This bed can be traced southward into the valley of the North Fork where it crops out on the west side of a fault that crosses the river at a large beaver dam	23
292. Sandstone and siltstone; Sandstone in lower two thirds of interval, pale reddish brown; siltstone greenish gray, thin-bedded, soft	22
291. Sandstone pale reddish brown, medium-grained and grayish red (10 R 4/2), fine-grained; all beds contain lumps of impure limestone	27
290. Sandstone, lower part pale red (10 R 6/2), coarse-grained, conglomeratic; upper part pale reddish brown, fine-grained; all beds strongly cross-bedded	22
289. Sandstone darker than grayish red (10 R 4/2), fine-grained, soft, lower beds silty; lumps of limestone and spots of moderate reddish-orange sandstone: irregular contact with Int. 290	6

	Feet
288. Sandstone moderate reddish orange, greener at base, coarse-medium-grained, scattered pebbles; cross-bedded (foreset beds dip W., NW)	23
287. Siltstone or mudstone grayish red (10 R 4/2), no visible bedding; lumps of limestone, dark reddish brown in sandstone matrix near top	7
286. Sandstone lower part grayish orange pink, coarse-grained, scattered pebbles; upper part pale reddish brown, medium-grained, limy lumps	8
285. Sandstone (70%) and siltstone interbedded; sandstone moderate reddish brown, fine-medium-grained, some beds grayish red (10 R 4/2); siltstone mainly covered, grayish red (10 R 4/2); limestone lumps with bright green coatings	55
284. Sandstone pale red (10 R 6/2), medium-grained, lumps of limestone near base	10
283. Siltstone darker than grayish red (10 R 4/2), lumps of limestone, very irregular bedding, thin beds of moderate reddish-orange sandstone; interval lenticular, undulant contact with Int. 284	4+
282. Sandstone (50%) and siltstone interbedded; sandstone pale red (10 R 6/2), medium-grained, cross-bedded; siltstone darker than grayish red (10 R 4/2), lumps of limestone	19
281. Siltstone darker than grayish red (10 R 4/2), micaceous	2
280. Sandstone lower part moderate orange pink, upper part pale red (10 R 6/2), medium-coarse-grained, a few thin-bedded layers in middle	18
279. Siltstone and limestone interbedded; siltstone similar to Int. 277; limestone bed .8 foot thick, near middle of interval, grayish red, weathers medium light gray	2
278. Sandstone moderate orange pink, medium-grained, limestone lumps and other pebbles near base	3
277. Siltstone darker than grayish red (10 R 4/2), micaceous, thin-bedded, soft; lumps of grayish-red limestone	1
276. Sandstone moderate reddish orange, medium-grained; lumps of limestone near base	22
275. Siltstone and sandstone interbedded; siltstone grayish red (10 R 4/2), soft, lumps of limestone; lens of sandstone moderate reddish orange in middle	3
274. Sandstone darker than moderate orange pink, medium-grained, cross-bedded, arkosic; lumps of grayish-red (5 R 4/2) limestone in upper half	11
273. Shale darker than grayish red (10 R 4/2), soft; irregular contact with Int. 274	1
272. Siltstone grayish red (10 R 4/2), thin-bedded, micaceous; top greenish gray (5 GY6/1.) limy. Sandstone dike in this interval	4
Offset south to large dry arroyo where bedrock is exposed.	
271. Sandstone pale red (10 R 6/2), medium-coarse-grained, cross-bedded, conglomeratic lenses and scattered pebbles of igneous and metamorphic rocks up to 1 inch in diameter	37
270. Covered (80%); siltstone and sandstone grayish-red (10 R 4/2), fine-grained, in float	70
269. Sandstone grayish pink, coarse-grained, conglomeratic, rounded fragments of igneous and metamorphic rock, lumps of dark sandstone weather out on surface	32
268. Covered; probably sandstone	7
267. Sandstone similar to Int. 265	10
266. Sandstone grayish pink, medium-coarse-grained, massive, lumps of limestone, medium light gray, scattered pebbles of igneous and metamorphic rock	8
265. Sandstone grayish red (10 R 4/2), very fine-grained, micaceous, thin-bedded, soft	16
264. Conglomerate pale red (10 R 6/2), matrix, coarse-grained sandstone; fragments, acid igneous rock, chlorite schist, and other metamorphic rock up to 5 inches in diameter. About a quarter mile south, this bed is a sandstone without pebbles	20
263. Covered; silty sandstone in upper 2 feet	50
Offset to southeast along hillside	
262. Covered; sandstone in float, similar to Int. 260, but not as conglomeratic	35
261. Siltstone pale reddish brown, with darker spots, weathers redder than moderate reddish-brown, sandy	2
260. Sandstone pale red (10 R 6/2), weathers darker, medium- and coarse-grained, arkosic, some beds conglomeratic, rounded fragments of igneous and metamorphic rock up to 2 inches in diameter	31
259. Sandstone moderate reddish brown, weathers lighter; fine- and medium-grained, weathers thin-bedded, soft	25
Basalt porphyry dike or sill, 6 feet thick.	
258. Sandstone similar to Int. 256, but some darker, fine-grained beds	12
257. Covered	7
256. Sandstone moderate orange pink, medium-grained	15
255. Partly covered; shale grayish red (10 R 4/2), silty, soft	5
254. Sandstone moderate orange pink, weathers darker, calcareous, lumps of grayish-red (10 R 4/2) limestone, weathers pinkish gray; upper half of interval contains lenses of subangular and rounded pebbles of igneous and metamorphic rock up to 1 inch in diameter	48

	Feet
253. Sandstone pale brown, fine-grained, silty, micaceous, thin-bedded	1
252. Sandstone pale brown (5 YR 5/2), weathers grayish red (10 R 4/2), coarse-grained, arkosic, cross-bedded, with beds of grit	35

Offset to the east bank of the North Fork of the Purgatoire River about .5 mile northwest of the confluence of the West Fork and the North Fork. Section begins about 30 feet above stream level.

251. Covered; few outcrops observed. Slabs of greenish-gray and pinkish-gray sandstone in float. Possibly some of the section below is duplicated in this interval; no uniformity of dip. 5000 ±feet.	

Fault, east side downthrown. Crosses West Fork of the North Fork of Purgatoire River just upstream from glacial moraine.

250. Sandstone mainly pale red (10 R 6/2), medium-coarse-grained, arkosic	40
249. Sandstone (80%) and siltstone interbedded; sandstone dark greenish gray and grayish orange pink, fine-grained, feldspathic	70
248. Sandstone grayish orange pink, weathers moderate yellowish brown, medium-grained, arkosic, breaks of darker siltstone	3
247. Shale dark gray, silty	1
246. Limestone medium gray, weathers moderate yellowish brown, very silty, dolomitic especially in lower part, middle 2 feet contain medium dark gray fragments that may be of algal origin	6
245. Sandstone (80%) and siltstone interbedded, dark reddish brown, mottled with pale green, thin irregular bedding, irregular lumps and ridges on bedding planes	22
244. Siltstone; lower part similar to Int. 242; upper part dark reddish brown; greenish-gray, silty limestone nodules	2
243. Sandstone (60%) and siltstone, pale brown; sandstone fine-grained, thin-bedded	18
242. Siltstone light gray, weathers moderate yellowish brown	2
241. Sandstone (50%), siltstone, and shale, mottled dark reddish brown and pale brown; sandstone fine-grained, calcareous, some beds have oscillation ripple marks which strike N.5° E	42
240. Sandstone with thin beds of siltstone, dark reddish brown	8
239. Siltstone (80%) and shale dark reddish brown, soft	6
238. Sandstone dark reddish brown, with lighter bands, fine-grained, feldspathic	10
237. Siltstone dark reddish brown, soft, some beds conglomeratic, pebbles of sandstone up to 2 inches in diameter	5
236. Sandstone dark reddish brown, fine-grained	7
235. Sandstone mottled dark reddish brown and dark greenish gray, fine-grained, feldspathic	10
234. Sandstone and siltstone grayish red and dark reddish brown; sandstone fine-grained, feldspathic, shows contemporaneous deformation	60
233. Partly covered. Float and scattered outcrops indicate red sediment. Below this interval strata are dominantly gray	300±

Offset to the north wall of the West Fork of the North Fork of the Purgatoire River, just below timberline, on base of red sequence.

232. Covered. Float consists of sandstone, light gray, weathers moderate yellowish brown. Interval is overlain by red beds	40
231. Sandstone (70%) and siltstone interbedded; sandstone pale brown and medium gray, medium-grained; siltstone dark greenish gray and grayish red (5 R 4/2)	110
230. Siltstone (90%) and limestone interbedded; siltstone greenish gray; limestone medium gray, sandy	5
229. Sandstone light gray, conglomeratic, arkosic at base	10
228. Siltstone grayish red (5 R 4/2), thin-bedded, soft	17
227. Sandstone pale brown, fine-grained, feldspathic, hard	6
226. Siltstone dark greenish gray, weathers dark reddish brown	11
225. Sandstone medium gray, fine- medium-grained, hard	15
224. Shale olive gray (5 Y 4/1), soft	6
223. Sandstone dark greenish gray, hard	15
222. Limestone and shale; limestone dark gray, weathers moderate yellowish brown; muddy slabby; shale medium gray and light olive gray, soft; near top are medium gray limestone nodules	17
221. Sandstone dark greenish gray, weathers lighter, medium-grained	10
220. Siltstone dark gray, argillaceous, weathers fissile	5
219. Shale medium dark gray, becoming increasingly silty toward top	12
218. Limestone dark gray, weather brown, silty	0.5
217. Sandstone and siltstone interbedded, dark greenish gray	25
216. Sandstone (or sandy limestone) medium dark gray, very limy, upper part weathers soft	3
215. Sandstone and siltstone interbedded, dark greenish gray, weathers slabby	60

Offset to the south wall of the West Fork of the North Fork of the Purgatoire River. Begin section about 725 feet stratigraphically above the sandy limestone (Int. 191) which crops out in the bottom of the valley. Measure section up the south wall to the top of cliff.

214. Sandstone gray* becomes increasingly red toward top, medium- and fine-grained, micaceous. This bed lies above timberline about 360 feet west of a cairn	

* Names of colors in Intervals 1–214 are not standard.

	Feet
on the divide between tributaries of Whiskey Creek, and of the West Fork of the North Fork of the Purgatoire River	47
213. Mainly covered; shale black, and soft sandstone	6
212. Sandstone dark greenish gray weathers tan, fine- and medium-grained; grains of pink, white and colorless quartz and a green mineral. Bands of dark red, 4 feet thick at 12 and 40 feet above base; band of dark gray silty shale 5 feet thick at 89 feet above base	98
211. Shale dark gray, silty, with small nodules of muddy limestone	5
210. Sandstone lower 24 feet dark purplish red, fine-grained; upper part gray, weathers tan, fine- and medium-grained	45
209. Siltstone and limestone interbedded; siltstone brown, soft; limestone purplish brown, nodular	6
208. Sandstone dark gray with red streaks, weathers light brown, fine-grained	15
207. Siltstone and limestone interbedded; siltstone light gray, sandy; limestone medium gray, finely crystalline, nodular at top and bottom, a thin bed in middle of interval	9
206. Sandstone, interbedded hard and soft layers; ledges greenish gray, weathers brown, fine-grained, irregular bedding, hard; saddles dark gray, micaceous, silty, soft; 1 foot of dark red, limy sandstone at top	21
205. Sandstone dark gray, weathers greenish gray and tan, fine-grained; a dark-red band 3 feet thick, 27 feet above base; upper 20 feet covered	56
204. Sandstone and limestone; sandstone light gray, fine-grained, thin-bedded; limestone gray, irregularly bedded, sandy	1
203. Sandstone dark gray, weathers greenish gray and light brown	23
202. Sandstone dark red, medium-grained, lower half thin-bedded, shaly; upper half mottled, thicker-bedded	14
201. Sandstone purplish brown and greenish gray, weathers dark gray, fine-grained, noncalcareous; lumps of dark red shale; ripple marks	137
200. Covered; possibly light gray sandstone	75
199. Sandstone and shale interbedded; sandstone fine-grained, thin ledges; makes saddle on ridge	15
Thickness of Sangre de Cristo formation	9548.9±

Madera formation

Whiskey Creek Pass limestone member

198. Sandstone dark gray, weathers darker; lower part fine-grained, limy; upper part might be called a sandy limestone, with pelecypods	12
197. Shale gray, weathers same, soft	2
196. Sandstone (or sandy limestone, grades laterally northward into limestone), gray, weathers, light gray with tan streaks, very limy, fine-grained, very cross-bedded, irregularly bedded	25
195. Mainly covered; some gray shale	3
194. Sandstone gray, weathers light brown, banded with streaks of brown and tan; fine-grained, calcareous, thin beds of limestone which are nearly a coquina of *Derbyia* sp., *Composita subtilita*, *Myalina* sp	12
193. Limestone similar to Int. 191, contains *Pseudorthoceras* sp	15
192. Mainly covered; brownish-gray shale and possibly sandstone	20
191. Limestone light gray, weathers same, very sandy, cross-bedded; coarse grains of white quartz, and brown and tan silty layers weather out in relief; dark oölites in several layers near top. Several beds contain *Myalina* cf. *M. cuneiformis*, *Edmondia* sp., steinkern of *Euphemites* sp., *Domatoceras* sp., *Ephippioceras* sp. This bed resembles the Jacque Mountain limestone but is more sandy	46
190. Sandstone greenish gray, with manganese oxide coatings, grades laterally into limestone; forms cliff	9
189. Limestone (grading laterally into sandstone) light gray, weathers same; medium crystalline, very sandy; on some beds coarse-grained quartz weathers out in relief; contains *Fusulina novamexicana*, *Composita* sp., gastropods	10
Thickness Whiskey Creek Pass limestone member	154

Arkosic limestone member

188. Sandstone gray, weathers greenish gray and light gray; fine-grained, but some beds medium-grained, very limy; a few layers of light gray sandy limestone	42
187. Partly covered; shale gray, soft	4
186. Limestone light gray, weathers same, cross-bedded, lumps of gray limestone; crinoid columnals	13
185. Sandstone gray, weathers greenish gray; fine-grained	12
184. Limestone light gray, weathers same, very sandy	8
183. Sandstone gray, weathers greenish gray and brown; fine-grained, calcareous, limy layers contain crinoid columnals; forms high cliff	115
182. Shale dark gray, weathers greenish gray; silty, soft; lower part contains poorly preserved *Lioclema* (?) sp. (12% of individuals), fenestellid bryozoans (6%), *Marginifera muricatina* (6%), *Dictyoclostus* sp. (19%), *Linoproductus* sp. (12%), *Astartella* sp. (6%), *Glabrocingulum grayvillense* (32%), *Pseudorthoceras* cf. *P. knoxense* (6%)	5

	Feet
181. Limestone dark gray, weathers medium gray; finely crystalline, muddy; small rosettes, about 2 inches in diameter, on bedding planes, may be of algal origin	1
180. Sandstone medium gray, weathers greenish gray and tan, fine-grained, calcareous, dark gray in top 1 foot	14
179. Sandstone dark red, fine-grained, thin bedded, micaceous, current ripple marks, current from NW	3
178. Sandstone gray, weathers greenish gray, purplish gray, and brown; very fine-grained, calcareous; breaks of fissile gray shale	54
177. Sandstone (50%) and shale interbedded; sandstone gray, weathers greenish gray and brown; fine-grained; shale gray, fissile, silty, raindrop impressions	45
176. Shale gray, weathers greenish gray and dark reddish brown, fissile; calcareous, scattered nodules of limestone	9
175. Limestone dark gray, weathers same; medium crystalline, wavy bedding	2
174. Sandstone and shale interbedded similar to Int. 163, but lacks plant remains; 10 foot band of light gray near top	56
173. Siltstone light greenish gray, very thin-bedded	5
172. Limestone light gray, weathers same, medium crystalline	3
171. Sandstone dark gray, weathers brown and greenish gray; partly thin-bedded and partly thick-bedded	20
170. Limestone dark gray, weathers light bluish gray; finely crystalline, somewhat silty and micaceous, wavy bedding	3
169. Sandstone and shale similar to Int. 163	22
168. Siltstone, shale and limestone similar to Int. 166, but contains more siltstone	14
167. Sandstone and shale similar to Int. 163, but lacks plant remains	9
166. Shale and limestone interbedded; shale dark gray, weathers very light gray; very fissile, calcareous, wavy bedding, limy nodules; limestone dark purplish gray, weathers brown, in 6 inch beds; thin siltstone beds	14
165. Sandstone and shale similar to Int. 163	5
164. Limestone dark gray, weathers brown; finely crystalline	2
163. Sandstone (90%) with thin shale breaks; sandstone gray, weathers brown and greenish gray brown; some beds mottled tan, fine-grained; plant remains; shale black. Forms large knoll on ridge	84
162. Sandstone (50%) and shale interbedded; sandstone gray, weathers brown and grayish brown; shale black, fissile, silty; oscillation ripple marks which strike E.; angular discordance with Int. 163	75
161. Shale dark gray, fissile, silty; lower part soft, upper part hard	23
160. Limestone medium gray, weathers buff gray; finely crystalline, muddy, blocky fracture, top 2 inches dolomitic and weathers brown	11
159. Shale dark gray, fissile, pyritic, silty; echinoid spines, worm trails, *Welleralla osagensis* var. *matura*, *Glabrocingulum grayvillense*	20
158. Sandstone medium gray, weathers grayish brown and greenish gray brown; fine-grained, a few thin beds of dark, fissile shale near base	18
157. Shale dark gray, silty with thin beds of dark gray limestone, weathers brown	33
156. Sandstone medium gray, weathers light gray (200 feet to south white with gray limestone fragments); medium-grained; has reddish-gray calcareous cement	7
155. Shale dark gray, thin sandy brown limestone at top	10
154. Limestone dark gray, weathers brown; finely crystalline, dolomitic	1
153. Shale (90%) and sandstone interbedded; shale black, fissile; sandstone mainly in lower part of interval, gray, weathers brown; fine-grained	49
152. Sandstone medium gray, weathers nearly white; medium-grained, slabby, seems to pinch out within 20 feet to south	0-5
151. Shale black, weathers brown; micaceous, silty near top, limestone nodules resembling septarian concretions	40
150. Shale, siltstone, and sandstone; shale and siltstone dark gray; sandstone light gray, fine-grained, near base of interval	45
149. Sandstone light gray, weathers greenish gray, fine-grained	5
148. Covered	10
147. Sandstone (80%) and shale interbedded; sandstone gray weathers greenish gray; fine- and medium-grained; shale black	20
146. Siltstone dark gray, weathers same, limy, thin shale breaks	12
145. Shale (80%) and siltstone interbedded; shale medium gray, soft; siltstone weathers brown, wavy bedding, shows swash-marks; a few thin beds of gray limestone; contains *Stereostylus* sp. (37% of individuals), echinoid spines (13%), *Crurithyris planoconvexa* (13%), *Composita subtilita* (18%), *Glabrocingulum grayvillense* (5%), *Euphemites villatus* (13%)	45
144. Limestone (80%) and shale interbedded; limestone dark gray, weathers brown and gray, gray portion has lumpy bedding; shale light gray	5

	Feet
143. Sandstone gray, fine-grained beds weather greenish gray, coarse-grained beds weather tan and light gray; conglomeratic; a few breaks of dark silty shale, especially near base; plant remains in fine-grained beds	90
142. Shale and siltstone interbedded, grading up into siltstone and sandstone; the finer the grain-size, the darker; sandstone light gray, fine-grained	25
141. Covered; probably dark gray shale	5
140. Limestone gray, weathers brown, fine-grained, silty, contains gastropods	2
139. Siltstone dark gray, weathers lighter; thin-bedded, very limy; contains worm trails (10% of individuals), *Euphemites blaneyanus* (12%), *Cymatospira monfortianus* (42%), *Glabrocingulum grayvillense* (12%), *Soleniscus brevis* (12%), high-spired gastropods (12%)	57
138. Mainly covered; siltstone and shale, dark gray	40
137. Siltstone dark gray, weathers dark greenish gray, limy	10
136. Covered; probably dark shale	13
135. Partly covered; limestone dark gray, weathers tan; finely crystalline, probably dolomitic, irregularly shaped dark-gray spots on surface, probably several shale breaks in interval	25
134. Covered; probably shale	15
133. Siltstone and shale dark gray, thin-bedded; limy	22
132. Partly covered; sandstone and shale; sandstone light gray, weathers tan; coarse-grained, bed near top of interval another near base; shale dark, mainly in float	25
131. Limestone light gray, weathers buff; finely crystalline, dolomitic, contains silicified fossils	6
Perhaps a fault through saddle	
130. Siltstone dark gray, weathers dark greenish gray; thin-bedded, shaly, micaceous, very limy	55
129. Shale dark gray, silty, soft, mainly covered	25
128. Limestone gray, weathers banded with silty layers lighter gray, and crystalline layers darker, color bands 1–2 inches thick	6
127. Shale dark gray and black, former silty, latter fissile; layers of gray limestone near middle of interval	26
126. Sandstone gray, weathers limonite-brown and gray, fine-grained	2
125. Limestone dark gray, lower part weathers light gray, thin-bedded, upper part weathers darker gray, thicker-bedded; all finely crystalline; contains *Mesolobus mesolobus*, numerous productid spines, large flat-spired gastropod in lower part of interval	26
124. Shale (70%) and limestone dark gray; shale silty; limestone muddy, thin-bedded; interval very fossiliferous, *Mesolobus mesolobus* (11%), *Chonetes granulifer gibbosus* (13%), *Chonetina flemingi* (3%), *C. flemingi crassiradiata* (3%), *Marginifera muricatina* (41%), *Spirifer opimus* (3%), *Punctospirifer kentuckyensis* (3%), *Composita subtilita* (3%), *Astartella* sp. (3%), *Euphemites vittatus* (3%), *Steroceras* sp. (3%), *Petalodus* sp. (3%), other fish teeth (7%)	35
123. Sandstone gray, fine- and coarse-grained; the former contain plant remains, the latter conglomeratic with subangular fragments of quartz and white feldspar	40
122. Partly covered; shale dark gray and black, fissile	12
121. Sandstone light gray, weathers tan and greenish gray, lower part coarse-grained, conglomeratic, upper part fine-grained, with shale breaks	12
120. Partly covered; a 1-foot bed of limestone, dark gray, weathers lighter near top of interval	4
119. Sandstone gray, weathers greenish gray, medium-grained, quartzitic, thin breaks of gray shale	11
118. Sandstone (or limestone) gray, very limy, fine-grained, lumps and nodules of gray limestone up to 1 inch in diameter	5
117. Shale black, silty; softer beds weather brown; limy layers with gastropods lie 30 and 35 feet above base of interval	47
116. Shale and sandstone; shale dark gray, soft; sandstone gray, weathers greenish gray, fine-grained	5
115. Sandstone gray, weathers tan and greenish gray; medium- and coarse-grained, scattered fragments of quartz, white feldspar and red jasper, at least one break of dark gray shale	17
114. Partly covered, shale gray and dark gray, former soft, latter fissile; sandy beds near top of interval	14
113. Limestone dark gray, weathers lighter; finely crystalline, scattered coarse grains of quartz; base dolomitic, weathers brown	2
112. Sandstone gray, weathers tan and greenish gray, fine- and medium-grained; partly covered	13
111. Shale dark gray, soft	6
110. Limestone dark gray, weathers lighter, finely crystalline, fossils replaced with white calcite; contains *Aulopora* sp., *Myalina* sp.	3
109. Sandstone gray, weathers greenish gray and tan, fine- and coarse-grained, thick-bedded; hard black shale at top	21

	Feet
Possibly fault through saddle.	
108. Limestone dark gray, weathers gray with brown edges; finely crystalline; contains *Chaetetes milliporaceous* in colonies up to 6 inches in diameter, fragments of brachiopods, *Myalina* sp.	1–2
107. Sandstone (grit) gray, weathers tan; coarse-grained, scattered pebbles of quartz, upper 1 foot dark greenish gray, soft	10
106. Covered; shale and sandstone, gray in float	15
105. Shale dark gray, silty, hard	6
104. Sandstone gray, weathers greenish gray and tan; medium- and coarse-grained, a few scattered pebbles of white quartz, feldspar, and red jasper	4
103. Covered	9
102. Limestone very dark gray, weathers same; finely crystalline	2
101. Covered	6
100. Sandstone similar to Int. 98	5
99. Covered, shale greenish gray, soft in float	6
98. Sandstone gray, weathers greenish gray and tan; fine- and medium-grained, micaceous, quartzitic	5
97. Partly covered; shale dark gray, silty, hard in float. (A trail across saddle in this interval)	36
Small fault in saddle.	
96. Limestone dark gray, weathers buff; dolomitic, finely crystalline, angular fragments of dark chert	3
95. Limestone dark gray, weathers dark bluish gray, brown at top; medium crystalline, calcite veinlets	16
94. Sandstone gray, weathers greenish gray and tan, fine- and medium-grained	6
93. Covered; ledges and float of gray, fine-grained sandstone and black fissile shale	25
92. Limestone dark gray, fossiliferous	5
91. Sandstone greenish gray, weathers white; medium-grained	3
90. Limestone and shale, gray	6
Offset from top of knoll southeast across fault.	
89. Limestone similar to Int. 87	15
88. Shale dark gray, very silty, poorly bedded, a few fossils	8
87. Limestone dark gray, lower part banded dark gray and tan, silty, gradational contact with Int. 86; upper part weathers brown, medium crystalline, sugary texture	4
86. Shale black, weathers dark gray; silty, fissile, with 6 inch beds of dark gray limestone which contain fragments of *Neospirifer* sp., scaphopods, pelecypods, *Straparollus* sp., *Soleniscus regularis*	20
85. Limestone dark gray, weathers lighter; medium crystalline; upper 1–2 feet brownish gray, weathers brown, sugary texture, dolomitic, with bifurcating marks on bedding planes; fragments of productids	15
84. Partly covered; dark gray limestone, weathers lighter; and olive green shale	10
83. Sandstone greenish gray, weathers same and tan; medium-grained	6
82. Siltstone olive green, soft	2
81. Limestone medium gray, weathers brownish gray, browner portions weather out in relief; medium crystalline	3
80. Sandstone (grit) gray, weathers green-gray or white; coarse-grained, very cross-bedded	7
79. Covered	5
78. Sandstone light gray, weathers light greenish gray and tan; medium- and coarse-grained, finer-grained and gray toward top	20
77. Sandstone medium gray, weathers greenish gray; fine-grained, micaceous, calcareous	10
76. Sandstone light gray, weathers tan; coarse-grained, quartzitic	9
75. Sandstone (60%) and shale; sandstone dark gray, weathers greenish gray; medium-grained, quartzitic; shale gray fissile, lenses of gray limestone	26
74. Sandstone gray, weathers white; coarse-grained, conglomeratic, with some fragments of red jasper	15
Section ends on limestone knoll on top of stream divide at the south side of cirque. Several N-S faults lie just east of knoll. Offset about 1 mile north to hillside west of saddle where trail crosses from the drainage of Culebra Creek to the North Fork of Culebra Creek.	
Thickness of Arkosic limestone member	2218
Gray limestone member	
73. Limestone dark gray, weathers lighter; medium crystalline, irregularly-shaped white siliceous nodules, a few fossils	18±
72. Sandstone gray, weathers white and greenish gray; white layers coarse-grained, cross-bedded; greenish-gray layers medium-grained, calcareous, with lenses and nodules of gray fossiliferous limestone	13
71. Shale and sandstone gray, weathers brownish gray; sandstone fine-grained, calcareous in upper 5 feet of interval	6
70. Limestone medium gray, medium crystalline, muddy, slabby; contains *Fusulina euryteines*, echinoid spines, crinoid columnals	1
69. Sandstone greenish brown, fine-grained	2
68. Limestone similar to Int. 66, but contains calcite veinlets and is more fossiliferous	26
67. Shale and sandstone greenish gray; sandstone fine- and medium-grained	3

	Feet
66. Limestone medium gray, medium crystalline, irregular bedding, slightly muddy	11
65. Partly covered; gray shale in float and ledges of gray limestone; contains cup corals, red productids, *Crurithyris* sp.	15
64. Grit gray, weathers tan, quartzitic	3
63. Shale dark gray, fissile	6
62. Conglomerate gray, weathers greenish gray, matrix coarse-grained sandstone; fragments of subangular quartz up to 2 inches in diameter	3
61. Shale and sandstone greenish gray; sandstone fine-grained, mainly near top	5
60. Limestone dark gray, weathers same; lumpy bedding, jagged surface	2
59. Shale and sandstone; shale light gray with a thin nodular gray limestone near middle of interval; sandstone olive green	7
58. Sandstone light gray, weathers same with tan edges, medium- and coarse-grained, coarse-grained part conglomeratic, fragments of quartz and feldspar up to 1 inch in diameter	3
57. Limestone dark gray, weathers brownish gray; silty; nodules of gray limestone in some beds	8
56. Partly covered; gray shale and thin gray limestone	6
55. Limestone dark gray, weathers lighter; medium crystalline, lower part thin-bedded, upper part massive with scattered grains of quartz	17
54. Sandstone gray, weathers greenish gray; fine-grained, calcareous	4
53. Shale and limestone; shale dark gray, silty, fissile; limestone dark gray, weathers lighter, rubbly; sandy at base of interval. A 2-foot bed at top of limestone contains *Fusulina laosensis*, *Marginifera scintillata*, *Composita* cf. *C. ovata*	20
52. Limestone dark gray, weathers brownish gray; very sandy, conglomeratic in upper part; at top of interval a gray limestone with black algal(?) markings. (Intervals 47–52 form a cliff.)	15
51. Shale dark gray, fissile	3±
50. Limestone dark gray, weathers lighter, nodular, with breaks of gray shale, fossiliferous	2
49. Partly covered; near top some gray sandstone, weathers brown, limy	10
48. Limestone gray, weathers light gray, rough surface	1
47. Sandstone light gray, weathers greenish gray, medium- and coarse-grained	8
46. Partly covered; limestone and shale interbedded; limestone dark gray, weathers brownish gray; medium crystalline, silty, with gray crystalline nodules; fossiliferous; upper 6 feet greenish-gray limy siltstone	30
45. Grit light gray, weathers lighter, much coarse-grained white quartz and feldspar; partly covered	30
44. Partly covered; gray shale in float, upper 5 feet gray shale and siltstone	20
43. Limestone gray, weathers bluish-gray, medium crystalline	1
42. Limestone dark gray, weathers brownish gray; silty, with gray crystalline nodules, fossiliferous; upper 6 feet greenish gray limy siltstone	30
41. Limestone dark gray, weathers same, medium crystalline, coarse grains of quartz weather out on surface	1
40. Sandstone light gray, weathers blue greenish gray; medium-grained with scattered larger grains, fragments of white feldspar; noncalcareous; forms of cliff	51
39. Shale and limestone black; shale silty; limestone nodular; a coquina of cup corals	10
38. Sandstone and shale gray, weathers light olive green; sandstone medium- and coarse-grained, mainly quartz, hard; shale mainly at base, soft	10
37. Sandstone (60%) and shale interbedded; sandstone pinkish red and gray, medium- and fine-grained, cross-bedded, grains of a green mineral; shale dark red, with nodules of gray limestone 3 feet below top of interval; angular discordance with Int. 38	21
36. Shale gray, micaceous, soft	6
35. Limestone light gray, weathers brownish and greenish gray with pitted surface; medium crystalline, hard	5
34. Limestone light gray, weathers greenish gray; silty, nodules of gray nonsilty limestone, fossiliferous; gradational contact with Int. 33	9
33. Shale dark gray, weathers brownish gray; fissile, much mica; contains worm trails, *Mesolobus striatus* (8% of individuals), *Marginifera muricatina* (15%), *M.* sp. (8%), *Spirifer rockymontanus* (8%), *Neospirifer* cf. *N. triplicatus* (15%), *Dictyoclostus* sp. (15%), *Linoproductus* sp. (15%), *Astartella vera* (8%)	18
32. Limestone dark gray, weathers brownish gray; finely crystalline, muddy, many thin layers of limy shale, and a few nodular layers; many *Dictyoclostus* sp.	21
31. Sandstone (75%) and shale dark gray, weathers greenish gray; sandstone fine-grained, micaceous, calcareous; shale hard, fissile	8
30. Limestone dark gray, weathers same; irregular bedding, lumpy; thin shale breaks weather readily resulting in rough surface; contains *Marginifera*	

	Feet
sp., productids, *Composita* sp., gastropods	6
29. Shale black, weathers greenish brown; fissile, limy, thin beds of dark sandy limestone, fossiliferous	16
28. Limestone dark gray, weathers brownish gray; muddy, blocky fracture; contains cup corals (3% of individuals), *Orbiculoidea missouriensis* (3%), *Derbyia crassa* (3%), *Mesolobus striatus* (25%), *Dictyoclostus portlockianus* (7%), *Marginifera muricalina* (25%), *M.*(?) sp. (3%), *Crurithyris planoconvexa* (7%), *Neospirifer triplicatus* (3%), *Spirifer occidentalis* (3%), *Composita subtilita* (7%), *Parallelodon obsoletus* (3%), *Edmondia* sp. (very large, 3%), *Straparollus* cf. *S. catelloides* (3%)	33
Thickness of Gray limestone member	528±

Sandia formation

Clastic member

	Feet
27. Sandstone (60%) and shale gray; sandstone medium-grained, quartzitic, in thin beds with shale breaks	35
26. Shale and sandstone similar to Int. 24.	14
25. Limestone dark gray, weathers brownish gray; some beds resemble algal growth	2
24. Shale (70%) and sandstone light red; sandstone fine-grained	28
23. Shale (50%) and sandstone light gray to greenish gray; small fossiliferous nodules in shale; sandstone medium-grained	8
22. Sandstone dark reddish brown	1
21. Sandstone and breccia greenish gray; sandstone coarse-grained; breccia in middle of interval; fragments of quartz, acid igneous rocks, chlorite schist up to 1 inch in diameter	19
20. Sandstone pinkish gray, weathers same, some beds shaly, soft	3
19. Shale (60%) and sandstone, medium and light gray; sandstone medium-grained	10
18. Limestone and shale; limestone very dark gray, weathers brown; sandy; shale in very thin beds; contains productid spines, *Composita* sp., *Bellerophon crassa*, small high- and low-spired gastropods	3
17. Sandstone light gray, fine-grained, thin-bedded, upper part quartzitic, lower 1 foot coarse-grained	8
16. Shale and sandstone; shale dark gray; sandstone gray, weathers greenish gray; forms a 1 foot bed at top of interval	14
15. Sandstone medium gray, medium-grained, quartzitic, with thin greenish gray shale breaks; upper 1 foot weathers reddish gray	25
14. Shale dark gray, muddy, weathers slabby; contains bryozoans (7% of individuals), *Meekella striatocostata* (1%), *Echinoconchus semipunctatus* (1%), *Dictyoclostus portlockianus* (42%), *Composita subtilita* (24%), *Nuculana bellistriata* (1%), *Myalina wyomingensis* (1%), *Pinna* sp. (1%), *Fasciculiconcha knighti* (1%), *Schizodus cuneatus* (1%), *S.* sp. (1%), *Edmondia* sp. (3%), *Pharkidonotus pericarinatus* (4%), *Angyomphalus minutus* (1%), *A.* cf. *A. umbilicatus* (4%), *Pseudorthoceras knoxense* (4%), *Ameura*(?) *trinucleata* (1%)	15
13. Sandstone (70%) and shale gray; sandstone fine- and medium-grained, some beds pinkish gray; a few thin beds of shale, fissile, nonmicaceous	25
12. Shale (50%) and sandstone; shale dark red; sandstone pinkish gray, weathers greenish gray; fine-medium-grained in several beds	6
11. Shale and sandstone; shale gray; sandstone in 1-foot bed at base, greenish gray, fine-grained with muscovite grains	8
10. Shale (70%) and sandstone dark red; sandstone coarse-grained, with quartz and chlorite grains; beds about 1 foot thick	27
9. Shale (80%) and sandstone gray; sandstone fine-grained, in several thin beds.	7
8. Shale dark red, with sandstone pinkish red, weathers gray, coarse-grained, in to 1.5 feet	5
7. Shale gray, with thin gray, fine-grained, micaceous sandstone at top	4
6. Breccia pink, weathers greenish gray, quartzitic, fragments of quartz up to 3 inches in diameter	2
5. Shale dark red, micaceous; top layer contains gray siliceous nodules up to 2 inches in diameter	9
4. Shale (75%) and sandstone; shale gray in lower part, dark red above, micaceous; sandstone light gray and brownish red, medium-grained, subangular grains of quartz and chlorite, thin beds	5
3. Shale light gray, scattered coarse, subangular grains of quartz	3
2. Sandstone and shale; sandstone similar to Int. 1; shale dark reddish brown, muddy, sandy	17
1. Sandstone buff and dark reddish brown, coarse-grained, angular grains of quartz, no feldspar, blocky fracture	10
Thickness of Clastic member	313
Total thickness of late Paleozoic	11,645.9

Possible fault between Int. 1 and Precambrian granite.

Section begins on saddle about three quarters of a mile north of the west portal of abandoned tunnel under Whiskey Creek Pass, Costilla County, Colorado.

Arkansas River Section

Section of the late Paleozoic strata measured in the Arkansas River valley between Wellsville and the vicinity of Howard, Fremont County, Colorado.

Feet

Top of section.

Section ends at a fault which brings the granite up against the red beds, on the west side of a high spur, S.32° E. from an abandoned ranch house which is located on the south side of the second large tributary on the east side of Badger Creek, about 4 miles airline north of Howard.

Sangre de Cristo formation.

Interval

471. Partly covered; sandstone greenish gray (5 GY 6/1)*, with brownish-gray coatings, fine- and medium-grained, calcareous, soft 62
470. Sandstone and siltstone greenish gray (5 GY 6/1) and grayish red (10 R 4/2); sandstone medium-grained; at top of interval grayish-red nodular limestone, weathers dark yellowish brown 62
369. Sandstone similar to Int. 467 20
368. Partly covered; sandstone dark greenish gray, medium- and fine-grained, soft 34
367. Sandstone weathers yellowish gray (5 Y 7/2), coarse-grained, feldspathic, thin beds of dark olive gray shale, contains plant remains 19
466. Siltstone and limestone; partly covered; siltstone dark greenish gray (5 GY 4/1); limestone gray, weathers dark yellowish brown in a bed 10 feet below top 28
465. Sandstone darker than light greenish gray (5 G 6/1), coarse-grained, feldspathic, scattered fragments of pink feldspar and quartz; calcareous, soft .. 90
464. Sandstone and siltstone interbedded; sandstone greenish gray (5 GY 6/1), fine- and coarse-grained; siltstone yellowish gray (5 Y 7/2) and pale red (10 R 4/2); top layer red, with limestone lumps 125
463. Covered 17
462. Sandstone probably darker than light greenish gray, weathers grayish orange, coarse-grained, conglomeratic, forms last hogback 39
461. Sandstone darker than light greenish gray (5 G 8/1), medium- and coarse-grained, cross-bedded (foreset beds dip E.); on west side of hogback 44
460. Siltstone and limestone (10%) interbedded; siltstone dark reddish brown, thin bedded; limestone grayish red, weathers dusky yellowish brown, nodular, two beds of dark shale 1 foot thick, at top 95
459. Covered 98
458. Sandstone and siltstone greenish gray; sandstone medium- and coarse-grained, feldspathic 30
457. Covered 30
456. Sandstone darker than light greenish gray (5 G 8/1), coarse-grained, arkosic, conglomeratic, rounded fragments of quartz, feldspar and granite up to 1 inch in diameter 9
455. Siltstone brownish gray, thin-bedded, micaceous, with grayish-red (5 R 4/2) limestone lumps in upper part 30
454. Sandstone grayish orange pink, weathers darker, coarse-grained, calcareous, basal edgewise conglomerate of gray siltstone fragments 26
453. Covered; valley fill 206
452. Grit pale red (10 R 6/2), arkosic, calcareous, cross-bedded 2
451. Sandstone and siltstone interbedded; sandstone greenish gray, coarse-grained, arkosic; siltstone light greenish gray (5 G 8/1) with a few streaks of dark reddish brown; 64 feet above base a 2-foot bed of limestone nodules in greenish-gray siltstone 106
450. Sandstone greenish gray (5 G 6/1), fine-grained, thin-bedded below; coarse-grained, massive above; arkosic, cross-bedded, bands of small pebbles. (Forms hogback with prominent overhanging cliff) 30
449. Covered, soft layer 105
448. Sandstone and siltstone greenish gray; sandstone coarse- and fine-grained, calcareous, one bed of dark reddish-brown limestone nodules. (Crops out in valley) 56
447. Sandstone greenish gray (5 G 6/1) coarse-grained, arkosic, conglomeratic, with subangular fragments of granite up to 2 inches in diameter. (Forms crest of hogback) 64
446. Partly covered; chiefly sandstone greenish gray (5 GY 6/1), weathers lighter, chalky appearance, coarse- to fine-grained, thin-bedded, cross-bedded; beds of greenish-gray and grayish-red siltstone; about 5 beds of grayish-red (5 R 4/2) nodular limestone 461
445. Sandstone greenish gray (5 G 6/1), weathers darker than light greenish gray (5 GY 8/1), and pale red (10 R 6/2), coarse-grained, arkosic. (Forms crest of hogback) 26
444. Siltstone grayish red (10 R 4/2) and dark greenish gray (5 G 4/2, micaceous, thin-bedded 26
443. Sandstone greenish gray (5 G 6/1), weathers pale red (10 R 6/2); coarse-grained, arkosic, cross-bedded, weathers into large rounded "elephant rocks" 13
442. Sandstone and siltstone reddish gray (10 R 4/2); siltstone thin-bedded, micaceous; sandstone coarse-grained, conglomeratic, arkosic; one coarse-grained, hard bed about 40 feet above base 107
441. Sandstone greenish gray, weathers darker than grayish orange pink, coarse-grained, arkosic, soft; a fine-grained bed about 30 feet above base.

* Names of colors are those listed in *Rock Color Chart*, National Research Council, 1948.

	Feet
(Crest of hogback lies about 60 feet above base)	116
440. Covered; probably soft siltstone and sandstone	36
439. Sandstone greenish gray (5 G 6/1), weathers darker than grayish orange pink, coarse-grained	22
438. Sandstone and siltstone grayish red and grayish green; sandstone fine- and coarse-grained, soft. (Forms valley)	86
437. Sandstone greenish gray (5 G 6/1), coarse-grained, arkosic, noncalcareous, with beds of fine-grained sandstone, a soft silty bed 30–40 feet above base; top of interval coarse-grained, weathers darker than grayish orange pink	60
436. Sandstone and siltstone greenish gray (5 GY 6/1), calcareous, some beds have grayish-red limestone nodules and lumps	69
435. Sandstone greenish gray (5 G 6/1), coarse-grained, arkosic, noncalcareous, hard	21
434. Partly covered; chiefly sandstone similar to Int. 430, but has beds of grayish-red, brownish-gray, and greenish-gray siltstone	82
433. Sandstone similar to Int. 430	13
432. Sandstone and siltstone lighter than greenish gray (5 GY 6/1), and brownish gray; sandstone fine-grained	21
431. Siltstone and sandstone interbedded; siltstone grayish red (10 R 4/2), weathers with smooth surface; sandstone lighter than greenish gray (5 GY 6/1), cross-bedded	30
430. Sandstone greenish gray (5 G 6/1), coarse-grained, arkosic, soft, calcareous, base has fragments of Int. 429, and light greenish-gray shale	21
429. Sandstone and siltstone lighter than grayish red (10 R 4/2); sandstone fine-medium-grained	22
428. Siltstone grayish red (10 R 4/2), thin-bedded, 3-foot bed of lumpy limestone at top	30
427. Sandstone chiefly light brownish gray, coarse-grained, cross-bedded, feldspathic, soft	55
426. Sandstone similar to Int. 418, but with red siltstone fragments at base	46
425. Siltstone and sandstone greenish gray (5 GY 6/1), and grayish red (10 R 4/2), thin-bedded, micaceous; sandstone fine-grained, some red limestone nodules near top	37
424. Sandstone similar to Int. 418	23
423. Siltstone and sandstone greenish gray (5 GY 6/1), and dark reddish brown, thin-bedded; sandstone fine-grained, some limestone nodules in a red bed at top	32
422. Sandstone similar to Int. 418, top grayish red	46
421. Covered; grayish-red and greenish-gray siltstone in float	14
420. Sandstone similar to Int. 418	41
419. Covered; perhaps siltstone, greenish gray, soft	22
418. Sandstone greenish gray (5 G 6/1), weathers grayish orange pink, coarse-grained, arkosic, cross-bedded, conglomeratic, fragments of granite up to 1 inch in diameter. (Forms large hogback)	46
417. Siltstone and sandstone (20%), greenish gray (5 GY 6/1) and grayish red (10 R 4/2) in bands 30–50 feet thick, thin-bedded, cross-bedded; sandstone fine-grained; a few beds of lumpy limestone in red layers	212
416. Siltstone and sandstone dark reddish brown and greenish gray (5 GY 6/1), a few beds of lumpy limestone; a 30-foot band of greenish-gray siltstone near middle and at top of interval	90
415. Sandstone greenish gray (5 GY 6/1), coarse-grained, arkosic, conglomeratic, cross-bedded; upper 40 feet less resistant	59
414. Partly covered; ledges of sandstone greenish gray (5 G 6/1), weathers grayish orange pink; dark reddish-brown siltstone between ledges	60
413. Sandstone and siltstone brownish gray (5 GY 4/1), weathers greenish gray (5 G 6/1) and brownish gray. Some beds show tubes about a quarter inch in diameter filled with brownish-gray siltstone on weathered surface of greenish-gray rock	5
412. Sandstone greenish gray (5 G 6/1), fine- and coarse-grained interbedded. (Crest of small hogback lies 40 feet above base)	110
411. Partly covered; sandstone and siltstone greenish gray (5 GY 6/1); sandstone fine-grained, micaceous, probably a thin nodular dark red limestone at top.	60
410. Sandstone greenish gray (5 G 6/1), weathers grayish orange, coarse-grained, arkosic. (Forms cliff about 15 feet high in small hogback)	46
409. Partly covered; siltstone (90%) and limestone dark reddish brown; limestone lumpy, nodular, at top of interval	28
408. Sandstone greenish gray (5 G 6/1), coarse-grained, arkosic, conglomeratic, subangular fragments of quartz and granite up to 1 inch in diameter, fragments of fossil plants covered with malachite	39
407. Siltstone and sandstone dark reddish brown; sandstone lighter, fine-grained, micaceous	27
406. Covered. (Valley fill)	7
405. Sandstone probably pale green, weathers grayish orange, coarse-grained, arkosic, many mud cracks; siltstone	

layers near base weather grayish red (10 R 4/2). (Forms crest of large hogback)..... 107 Feet

404. Covered; probably soft siltstone and sandstone, weather moderate yellowish brown..... 24

403. Sandstone darker than pale green and dark greenish gray (G 5 4/1), former coarse-grained, latter fine-grained; arkosic..... 62

402. Sandstone and siltstone grayish red and greenish gray (5 G 4/1); sandstone fine-grained..... 16

401. Sandstone greenish gray (5 G 4/1) coarse- and fine-grained..... 46

400. Sandstone and siltstone grayish red (10 R 4/2), thin nodular limestone at top..... 27

399. Sandstone similar to Int. 397, but conglomeratic, containing subangular fragments of light red and moderate red granite up to 2 inches in diameter, hard..... 66

398. Sandstone and siltstone similar to Int. 396..... 16

397. Sandstone dark greenish gray (5 G 4/1), coarse-grained, arkosic..... 15

396. Sandstone and siltstone grayish red (10 R 4/2) with a few grayish-orange-pink beds; sandstone medium-grained, calcareous; at top, one foot bed of gray limestone, weathers dark yellowish brown. Sandstone dikes coming from Int. 395 in base of interval..... 102

395. Sandstone darker than pale green, weathers darker than grayish orange pink, coarse-grained, arkosic, conglomeratic; fragments of red siltstone near top..... 23

394. Sandstone and siltstone pale red (10 R 6/2) interbedded; sandstone fine-grained..... 52

393. Sandstone and siltstone grayish green (5 GY 6/1) and dark greenish gray (5 GY 4/1); sandstone fine- and medium-grained; siltstone thin-bedded; top bed 4 feet thick, massive..... 39

392. Covered; possibly dark red siltstone... 15

391. Sandstone and siltstone dark reddish brown, some beds light brownish gray; sandstone fine-grained..... 31

390. Sandstone greenish gray (5 GY 6/1), weathers grayish red (5 R 4/2), coarse-grained, cross-bedded..... 51

389. Partly covered; sandstone and siltstone brownish gray (5 YR 4/1) and dark reddish brown; sandstone medium-grained, soft; nodular limestone grayish red, weathers dark yellowish brown near top..... 43

388. Sandstone and siltstone dark reddish brown and grayish red (10 R 4/2); lumps of grayish-red limestone near top of interval..... 20

387. Partly covered dip slope; sandstone greenish gray (5 G 6/1), coarse-grained, arkosic, in ledges at top..... 47 Feet

386. Limestone dark gray, weathers moderate yellowish brown, medium crystalline, pink feldspar and quartz weather out on surface..... 1

385. Sandstone similar to Int. 383..... 19

384. Siltstone and sandstone dark greenish gray (5 GY 4/1), thin-bedded, gray limestone nodules in top 2 feet..... 27

383. Sandstone lighter than greenish gray (10 GY 5/2), coarse-grained, arkosic; gray limestone nodules interbedded in top. (Forms hogback)..... 11

382. Sandstone and siltstone (50%); sandstone pale green and dark grayish green (5 G 5/1), former coarse-grained, latter finer, some beds mud cracked; calcareous, hard; upper 15 feet fine-grained contains plant remains; nodular limestone at top in gray silty shale.... 117

381. Siltstone and sandstone dark reddish brown, soft; top 6 feet are greenish-gray (5 GY 6/1) siltstone and medium dark-gray limestone nodules..... 27

380. Sandstone probably pale green, weathers grayish orange and pale red (10 R 6/2)..... 27

379. Partly covered; sandstone and siltstone dark reddish brown; sandstone medium-grained, several dark-gray beds, weather dark yellowish brown; a few beds of limestone nodules..... 35

378. Sandstone lighter than pale green, weathers grayish orange, coarse-grained, becomes dark reddish brown at top... 39

377. Edgewise breccia, limestone fragments similar to those in Int. 376 in coarse sandstone matrix..... 1

376. Sandstone and siltstone dark reddish brown; sandstone medium-grained, scattered nodules of grayish-red (5 R 4/2) limestone; shaly near top..... 28

375. Sandstone probably pale green, weathers moderate yellowish brown, coarse-grained, conglomeratic, subangular fragments of quartz, feldspar, and pink granite; feldspathic; upper part softer, weathers grayish orange pink. (Forms second crest of double hogback)..... 55

374. Partly covered; sandstone and siltstone dark reddish brown below, greenish gray (5 GY 6/1) above; nodules of gray limestone in lower part, weather dusky yellow brown..... 51

373. Sandstone and siltstone; sandstone similar to Int. 372, but weathers pale red (10 R 6/2); siltstone dark grayish brown; softer unit than Int. 372. (Lies between crests of double hogback).... 43

372. Sandstone darker than pale green, weathers moderate yellowish brown; coarse-grained, arkosic, conglomeratic, rounded pebbles of pink granite, and feldspar up to 3 inches in diameter;

	Feet
contains plant remains covered with malachite and azurite. (Forms cliff in western crest of double hogback)	62
371. Siltstone and shale greenish gray (5 GY 6/1), and dark gray, soft; partly covered	31
370. Sandstone darker than pale green, weathers grayish orange pink, coarse-grained	27
369. Siltstone and sandstone grayish red (10 R 4/2); sandstone fine-grained, calcareous	27
368. Sandstone pale green and greenish gray (5 GY 6/1), coarse-grained, cross-bedded; thin lenses of dark reddish-brown siltstone	45
367. Partly covered; sandstone and siltstone pale brown (5 YR 5/2) and light olive gray (5 Y 6/1) where fine-grained; dusky yellowish green where coarse-grained; feldspathic, soft	180
366. Sandstone probably darker than pale green, weathers pale red (10 R 6/2)	20
365. Partly covered; soft siltstone with nodular gray limestone, weathers dark yellowish brown; several ledges of sandstone darker than pale green, coarse-grained	58
364. Sandstone darker than pale green, coarse-grained, conglomeratic, pebbles of quartz and orthoclase	19
363. Limestone grayish black, weathers dark yellowish brown, finely crystalline	1
362. Partly covered; ledges of sandstone, darker than pale green, weathers pale red (10 R 6/2), a few beds of gray siltstone; plant remains	68
361. Edgewise breccia medium gray, weathers moderate brown, matrix sandstone, angular fragments of limestone	1
360. Sandstone darker than pale green, coarse-grained, finer at top, arkosic	15
359. Limestone reddish gray (10 R 4/2) weathers darker than moderate yellowish brown, medium crystalline, silty	6
358. Sandstone and siltstone similar to Int. 357, but mainly grayish orange	35
357. Sandstone and siltstone darker than yellowish gray (5 Y 7/2), interbedded with discontinuous beds of grayish orange; sandstone fine- and medium-grained; a few beds of silty nodular limestone	129
356. Sandstone pale green, and greenish gray (5 Y 7/2); former coarse-grained, conglomeratic, fragments of subangular feldspar and granite up to 3 inches in diameter; latter contains *Calamites* sp. and other plants coated with malachite	27
355. Siltstone and limestone (40%); siltstone greenish gray (5 GY 6/1); limestone dark gray weathers moderate yellowish brown, lumpy	7
354. Sandstone and siltstone dark reddish brown; sandstone fine-grained, small lumps of gray limestone	19
353. Sandstone darker than pale green, fine- and coarse-grained; fine-grained beds dark grayish green (5 GY 4/1), with lumps of gray limestone	62
352. Siltstone and sandstone dark reddish brown; sandstone fine-grained; siltstone thin-bedded	15
351. Sandstone darker than pale green, weathers moderate yellowish brown, coarse-grained, feldspathic, conglomeratic; top very cross-bedded; thin lenses of fine-grained sandstone; contains plant fragments	50
350. Sandstone and siltstone; sandstone pale green, weathers browner, medium-grained; siltstone light olive gray (5 Y 5/2), thin-bedded	66
349. Siltstone and sandstone greenish gray (5 GY 6/1); sandstone medium-grained; partly covered	43
348. Sandstone and siltstone dark reddish brown, calcareous; sandstone medium-grained; fragments of gray limestone, weather moderate yellowish brown	31
347. Sandstone darker than pale green, weathers darker than grayish orange pink, coarse-grained, conglomeratic, subangular fragments of granite, quartz up to 2 inches in diameter; a few fine-grained, light olive gray (5 Y 5/2) beds. (Forms crest of large hogback)	52
346. Siltstone and sandstone interbedded, greenish gray (5 GY 6/1), micaceous; sandstone medium-grained	94
345. Siltstone dark reddish brown, micaceous, thin-bedded, a few beds of pale red (5 R 6/2), arkosic sandstone	33
344. Sandstone greenish gray (5 GY 6/1), weathers darker than grayish orange pink, medium- and coarse-grained, arkosic, cross-bedded	56
343. Edgewise breccia medium gray, limestone fragments weather dark yellowish brown in sandstone matrix	2
342. Sandstone greenish gray (5 GY 6/1), medium-grained, some beds very cross-bedded	29
341. Siltstone and limestone (10%), dark reddish brown below, medium gray above; limestone lumpy, very silty	10
340. Siltstone and limestone (10%) interbedded; siltstone light olive gray (5 Y 6/1); limestone medium gray, weathers same, nodular; a white soil that suggests the presence of gypsum	21
339. Sandstone pale green (10 G 6/2), cross-bedded, arkosic, conglomeratic, subangular fragments of quartz, pink feldspar, granite up to 1 inch in diameter; finer-grained, not conglomeratic near top	61

	Feet
338. Siltstone (70%), sandstone (20%) and limestone interbedded; siltstone greenish gray (5 GY 6/1), some soft beds but others hard and platey; sandstone same color, medium-grained, in ledges; limestone dark gray, thin beds and nodules	61
337. Sandstone lighter than light brownish gray (5 YR 6/1), medium-grained, in ledges; manganese oxide coatings on joint planes	28
336. Partly covered; limestone dark gray, weathers moderate yellowish brown, beds of shale with lumpy bedding	12
335. Sandstone light olive gray (5 Y 5/2), medium-grained, cross-bedded	42
334. Partly covered; sandstone and limestone; sandstone light olive gray (5 Y 5/2), fine-grained, in ledges; limestone dark gray, weathers moderate yellowish brown, finely crystalline, in at least three irregular beds	28
333. Sandstone greenish gray (5 GY 6/1), irregularly bedded at base, lower 25 feet fine-grained, thin-bedded, almost fissile; upper 45 feet coarse-grained, resistant; contains *Walchia* sp.	70
332. Siltstone dark reddish brown, mainly thin-bedded, shaly, calcareous	5
331. Sandstone greenish gray (5 G 6/1), weathers pale yellowish brown (10 YR 6/2), coarse-grained, arkosic, calcareous. (Forms crest of first hogback east of Badger Creek)	28
330. Covered	9
329. Siltstone and sandstone olive gray (5 Y 4/1); sandstone fine- and medium-grained, except for top 10 feet, the whole interval is soft and thin-bedded	38
328. Sandstone light olive gray (5 Y 5/2), medium- and fine-grained interbedded, 14 feet above the base this grades into grayish-red (10 R 4/2) sandstone, and 57 feet above the base this grades into limestone conglomerate with greenish-gray sandstone matrix	62
327. Siltstone (50%), sandstone (40%), and shale; siltstone and sandstone olive gray (5 Y 4/1), fine-grained; shale greenish black, shiny; plant remains	11
326. Sandstone grayish red (10 R 4/2) grading up into greenish gray (5 GY 6/1), fine- and coarse-grained, coarse layers conglomeratic, fragments of limestone; a few thin siltstone beds; interval alternates hard and soft layers	70
325. Limestone and siltstone olive gray (5 Y 4/1), weathers moderate yellowish brown, white efflorescence on surface	4
324. Siltstone (90%) and sandstone dark red, mottled with greenish gray (5 Y 6/1)	15
323. Sandstone and siltstone; sandstone greenish gray (5 GY 4/1) medium- and coarse-grained, chiefly in base of interval; siltstone slightly darker, contains a few nodules of gray limestone	20
322. Sandstone (70%) and limestone; sandstone dark greenish gray (5 GY 6/1); limestone medium gray, lumpy bedding	7
321. Sandstone greenish gray (5 GY 6/1) darker near top, fine- and medium-grained, fine-grained beds softer; *Calamites* sp. and other plant fossils	50
320. Limestone and siltstone (50%) dark reddish brown, limestone weathers medium gray, lumpy bedding	6
319. Sandstone and siltstone (20%) interbedded; siltstone dark reddish brown, chiefly near base; sandstone coarse-grained, grayish red (10 R 4/2), finer-grained layers dark reddish brown	68
318. Limestone and siltstone (30%) dark reddish brown, mottled with light greenish gray (5 G 8/1)	6
317. Siltstone and sandstone (30%) dark reddish brown, grading up into grayish red (10 R 4/2); sandstone medium-grained; siltstone calcareous	31
316. Limestone and siltstone (40%), dark reddish brown, weathers crumbly, lumpy bedding	4
315. Sandstone grayish red (10 R 4/2) and greenish gray (5 GY 6/1), medium- and coarse-grained, arkosic, conglomeratic, small pebbles of limestone	11
314. Sandstone greenish gray (5 Y 6/1), coarse-grained, arkosic conglomeratic, fragments of limestone, quartz, orthoclase up to 2 inches in diameter; streaks of dark mineral grains	9
313. Sandstone with limestone nodules, grayish red below, greenish gray (5 GY 6/1) above; limestone medium gray	17
312. Partly covered; sandstone and siltstone; sandstone grayish red (10 R 4/2), medium-fine-grained; siltstone dark reddish brown, a few gray limestone nodules	30
311. Limestone (40%) and siltstone dark reddish brown and medium dark gray; siltstone calcareous	4
310. Siltstone grayish red (10 R 4/2) and greenish gray (5 GY 6/1), micaceous	19
309. Limestone (60%) and siltstone, dark reddish brown and medium dark gray, weathers lighter; limestone lumpy	27
308. Sandstone grayish red (10 R 4/2), fine-grained	13
307. Shale (60%) and limestone; shale brownish gray (5 YR 4/1), silty; limestone dark gray, finely crystalline, nodular	13
306. Sandstone lighter than pale green (10 G 6/2), coarse-grained, cross-bedded, a few thin beds greenish black (5 GY 2/1), fine-grained	14
305. Siltstone (70%) and limestone; siltstone pale olive (10 Y 6/2); limestone medium gray, nodular	3

	Feet
304. Sandstone pale red (10 R 6/2) mottled with greenish gray (5 GY 6/1), fine-grained	11
303. Siltstone (70%) and limestone; siltstone greenish gray (5 GY 6/1); limestone medium gray, nodular	3
302. Sandstone (60%) and siltstone grayish red (10 R 4/2); sandstone medium- and coarse-grained, fragments of gray limestone; siltstone dark red	26
301. Shale and limestone dark reddish gray; shale silty; limestone nodular	16
300. Shale dark red below, greenish gray (5 G 6/1) above, silty; basal bed darker, wedges out to north; a few thin beds of dark-gray limestone; shale contains ganoid fish scales, bones of *Diadectes* sp., and pelycosaurs	8
299. Sandstone pale olive (10 Y 6/2) medium-grained, feldspathic, some layers very conglomeratic, subangular fragments of quartz and limestone	2
298. Limestone (70%) and shale; limestone medium gray, nodular with dark reddish-brown shale between nodules	16
297. Sandstone (70%) and shale; sandstone olive gray, fine-grained; shale grayish black, silty plant remains and reptile bones	2
296. Sandstone pale green (10 G 6/2), weathers greenish gray (5 GY 6/1), coarse-grained, feldspathic, conglomeratic, fragments of quartz and feldspar	12
295. Siltstone (90%) and limestone dark reddish brown except at base which is very dusky red; limestone medium gray and dark red, nodular, at top of interval	18
294. Sandstone similar to Int. 290, weathers pale red (10 R 6/2), contains lenses of soft siltstone	12
293. Sandstone (90%) and limestone interbedded; sandstone dark reddish brown, medium-grained, soft; limestone same color, weathers gray	20
292. Sandstone pale green (10 G 6/2), weathers medium yellow brown, coarse-grained, arkosic, cross-bedded, conglomeratic, streaks of black minerals grains	12
291. Siltstone (50%), sandstone (30%), and limestone interbedded; mainly dark reddish brown, soft; some sandstone beds grayish red (10 R 4/2), coarse-grained; limestone medium gray, in beds and nodules	57
290. Sandstone grayish red (10 R 4/2), coarse-grained, cross-bedded, conglomeratic, scattered fragments of limestone	4
289. Siltstone (70%) and limestone with a few beds of sandstone; dark reddish brown; limestone weathers medium gray	20
Offset north to mouth of first large tributary which enters Badger Creek from east.	
288. Sandstone pale green (10 G 6/2) and greenish black (5 GY 2/1), former coarse-grained, arkosic, latter fine-grained	45
287. Limestone (70%) and siltstone interbedded; dark reddish brown and medium gray, irregular beds and nodules; siltstone dark reddish brown, micaceous; sandy near top. Interval looks striped in stream bank	47
286. Sandstone olive gray (5 Y 4/1), weathers moderate yellowish brown at top; fine-grained, much cross-bedding, scour-and-fill, and lensing of beds; some beds of dark greenish-gray shale	15
Offset across Badger Creek on Int. 286	
285. Siltstone (80%) and limestone similar to Int. 282	6
284. Covered; probably chiefly sandstone gray and red, fine-grained. (Road on west side of Badger Creek)	20
283. Sandstone pale red (10 R 6/2), coarse-grained, conglomeratic, rounded fragments of red granite up to 4 inches in diameter, and angular dark reddish-brown siltstone and limestone up to 3 inches in diameter; arkosic, cross-bedded	26
282. Siltstone (80%) and limestone dark reddish brown; siltstone shaly, micaceous; limestone nodular	7
281. Sandstone grayish red (10 R 4/2), coarse-grained, conglomeratic, fragments of quartz and granite up to .5 inch in diameter; beds and pockets of very dusky red sandstone, finer-grained, cross-bedded	7
280. Siltstone, limestone, and sandstone; siltstone dark reddish gray, shaly, micaceous; sandstone pale red (10 R 6/2), near base of interval; limestone dark reddish brown, nodular, lumpy, a 2 foot bed near top	15
279. Limestone dark reddish brown, weathers medium light gray, medium cystralline, irregular bedding	2
278. Siltstone and limestone dark reddish brown; limestone nodular, some beds weather medium light gray	20
277. Sandstone and shale (50%); sandstone dark reddish brown, medium crystalline; shale pale reddish brown at base of interval	10
276. Sandstone light brownish gray (5 YR 6/1), weathers pale red (5 Y 6/2), coarse-grained, arkosic, cross-bedded, irregular contact with Int. 275	23
275. Siltstone and limestone dark reddish brown, micaceous; limestone nodular, lumpy bedding	14
Offset north on Int. 274 to east-west valley with willow trees on the west side of Badger Creek. This valley is south of the mouth of the first large tributary on the east side of Bader Creek.	
274. Sandstone darker than grayish blue green, weathers light olive gray (5 Y	

	Feet
6/1); coarse-grained, arkosic; basal 2 feet consists of hard siltstone, very dusky red	15
273. Sandstone, and nodular limestone similar to Int. 271	32
272. Limestone medium dark gray, weathers moderate yellowish brown; medium crystalline, irregular bedding	1.5
271. Sandstone and nodular limestone dark reddish brown; sandstone mainly fine-grained, some medium-grained beds. (Intervals 271, 272, and 273 are notably nonresistant to erosion)	35
270. Sandstone pale red (5 R 6/2), coarse-grained, arkosic, cross-bedded; streaks of black mineral grains	11
269. Siltstone and limestone similar to Int. 267	10
268. Sandstone darker than pale red (10 R 6/2), coarse-grained, arkosic, conglomeratic, fragments of quartz, and pink feldspar up to 1 inch in diameter	12
267. Siltstone and limestone interbedded, dark reddish brown; siltstone micaceous; limestone weathers light gray	18
Two faults which trend N.80° E. pass through here. Cross them in Int. 267.	
266. Sandstone greenish gray (5 G 6/1) with pinkish cast due to feldspar, weathers darker, coarse-grained, arkosic, conglomeratic; lenses and thin beds of siltstone brownish gray (5 YR 4/1) and darker than grayish green (10 G 4/2), micaceous	15
265. Shale and limestone (50%); shale very dusky red and light olive gray (5 Y 5/2); limestone dark reddish brown and medium gray, nodular	9
264. Sandstone very dusky red, fine-grained, arkosic	11
263. Limestone (60%) and siltstone similar to Int. 261, but some limestone weathers light gray	20
262. Sandstone dark reddish brown, medium-grained; one prominent ledge lighter than pale red (5 R 4/2), coarse-grained, with streaks of black mineral grains	25
261. Siltstone and limestone (50%); siltstone reddish brown, micaceous; limestone lighter than dark reddish brown; many lumpy, nodular beds	14
260. Sandstone dark reddish brown, mainly fine-grained, arkosic, cross-bedded, many step-like ledges	20
259. Sandstone and nodular limestone similar to Int. 257, but some beds of medium light gray limestone	20
258. Sandstone and siltstone; lower part sandstone dark reddish brown; upper part siltstone very dusky red	10
257. Sandstone and limestone (50%) interbedded; sandstone darker than dark reddish brown, fine-grained; perhaps some beds are siltstone; arkosic; limestone dark reddish brown, weathers light gray, nodular; irregular beds	41
256. Sandstone (80%) and siltstone interbedded; sandstone pale red (10 R 4/2), and dark reddish brown, medium- and coarse-grained; coarse-grained layers conglomeratic, pebbles as in Int. 254; siltstone very dusky red, micaceous	80
255. Limestone dark reddish brown, weathers light gray, finely crystalline, grains of quartz and feldspar weather out in relief on surface	1
254. Sandstone pale red (10 R 6/2) coarse-grained, arkosic, cross-bedded, conglomeratic, subangular fragments of quartz and granite up to 3 inches in diameter; lenses and pockets of dark reddish-brown and medium gray, calcareous sandstone	65
253. Sandstone (70%) and siltstone dark reddish brown; sandstone medium-grained, soft	37
252. Sandstone pale red (10 R 6/2), medium- and coarse-grained, cross-bedded, conglomeratic, fragments of granite up to 3 inches in diameter	50
251. Sandstone (50%), siltstone (30%), and limestone interbedded; sandstone dark reddish brown, medium-grained; siltstone very dusky red; limestone yellowish gray, in nodules and thin beds scattered through interval	20
250. Sandstone (60%) and siltstone interbedded; sandstone grayish red (10 R 6/2), and dark reddish brown, fine- and medium-grained; siltstone very dusky red; interval capped by hard sandstone	53
249. Sandstone similar to Int. 247	11
248. Sandstone dark reddish brown, medium- and fine-grained, calcareous	19
247. Sandstone pale red (10 R 6/2), medium- and coarse-grained, arkosic, cross-bedded	14
246. Sandstone (90%) and limestone interbedded; sandstone very dusky red, medium-grained, calcareous; limestone, impure beds and nodules in upper half of interval	28
245. Siltstone and limestone (50%); siltstone very dusky red; limestone light gray below, pale red (10 R 6/2) above, nodular, irregular bedding	24
244. Sandstone darker than pale red (5 R 6/2), coarse-grained, arkosic, cross-bedded, calcareous at base, conglomeratic in middle, rounded fragments of brownish-gray porphyry, and red granite up to 2 inches in diameter	59
243. Partly covered; sandstone and siltstone; dark reddish brown; sandstone medium-grained, forms 5 foot bed at base and scattered beds above	18
242. Limestone medium dark gray, weathers moderate yellowish brown, finely crystalline, very lumpy bedding	7

	Feet
241. Sandstone dark reddish brown and very dusky red, medium-grained, micaceous, arkosic, calcareous, two lenses of medium gray, lumpy limestone	38
240. Sandstone pale red (5 R 6/2), coarse-grained, arkosic, conglomeratic	33
239. Sandstone dark reddish brown, medium-grained, thin-bedded, soft	10
238. Siltstone olive gray (5 Y 4/1), micaceous, nonclacareous, undulant bedding; sandy in upper part	25
237. Sandstone and shale (30%) interbedded, dark reddish brown; sandstone medium- and fine-grained; 5-inch bed of limestone darker than medium bluish gray at top	10
236. Sandstone pale red (5 R 6/2), coarse-grained, arkosic, conglomeratic, fragments of red granite, and quartz up to 1 inch in diameter; contact with Int. 235 shows about 3 feet of relief; fragments of Int. 235 in base	12
235. Sandstone (60%), siltstone (30%), shale and limestone interbedded, dark reddish brown, micaceous; sandstone fine-grained; limestone in several 2 inch beds about 3 feet below top	14
234. Sandstone pale red (5 R 6/2), coarse-grained, arkosic, noncalcareous	9
233. Limestone medium dark gray, weathers lighter, finely crystalline, lumpy bedding, suggesting algal growth	1
232. Siltstone, sandstone, and limestone interbedded; siltstone and sandstone dark reddish brown, micaceous; sandstone medium-grained; limestone medium gray and dark reddish brown, silty, nodular	19
Offset to hillside north of east end of tunnel.	
231. Sandstone pale red (5 R 6/2), medium-grained	20
Thickness of Sangre de Cristo formation	8836.5

Minturn formation

230. Siltstone dark greenish gray below, grayish red (10 R 4/2) above; micaceous	33
229. Limestone dark gray, weathers lighter; finely crystalline, lumpy irregular bedding	5
228. Siltstone (90%) and limestone interbedded; siltstone dark greenish gray at base, dark reddish brown above; micaceous; limestone dark gray, in beds and nodules	39
227. Sandstone darker than dark greenish gray (5 GY 4/2), medium-grained; grains of white feldspar	8
226. Limestone dark gray, weathers lighter, medium crystalline, bedding irregular in lower beds, more regular above; fragments of black chert in upper 2 feet	8
225. Sandstone and siltstone similar to Int. 223	9
224. Limestone dark gray, weathers pale yellowish brown, medium crystalline, perhaps some beds are algal	6
223. Sandstone and siltstone similar to Int. 222, but contains beds of dark gray shale and limestone	9
222. Sandstone and siltstone light olive gray (5 Y 5/2) and pale olive; sandstone fine-grained, irregular bedding	24
221. Shale and limestone dark gray; limestone in thin beds and nodules	29
220. Limestone dark gray and grayish black, weathers yellowish gray (5 Y 7/2), finely crystalline, muddy, undulant bedding; edgewise breccia of limestone fragments at base; contains *Bakewellia parva* (?), *Stegocelia* sp., and a new genus of gastropod	6–8
219. Shale (70%) and limestone; shale grayish black, silty; limestone medium gray, finely crystalline, forms 14 inch bed in middle of interval	4
218. Sandstone (80%) and limestone, medium gray and brownish gray (5 YR 4/1); sandstone fine-grained, micaceous; limestone in 2-inch bed at base, and in 2-foot bed at top	11
217. Sandstone dark reddish brown, medium-grained, soft	19
216. Limestone (80%) and shale; limestone dark reddish brown in top and bottom beds, dark gray in middle beds, finely crystalline, irregular bedding; shale chiefly dark reddish brown	9
215. Sandstone and siltstone dark reddish brown; sandstone fine-grained; siltstone soft	19
214. Sandstone pale red (10 R 6/1) and slightly darker, medium- and coarse-grained, cross-bedded, streaks of black mineral grains	43
213. Sandstone and siltstone dark reddish brown, with a dark-gray band about 3 inches thick about 5 feet above base; sandstone medium-grained	30
212. Limestone dolomitic, light gray, weathers pale yellowish brown; finely crystalline, irregular bedding, calcite stringers; thin olive-gray shale at top	2
211. Sandstone dark yellowish brown at base, grades up into dark reddish brown, fine-grained, micaceous	21
210. Limestone dark gray, weathers lighter; finely crystalline, irregular bedding	1
209. Sandstone (80%) and shale; sandstone very dusky red and pale red (10 R 6/1), medium-coarse-grained, irregular bedding, shale very dusky red, at base	64
Offset to north side of fault on Int. 208.	
208. Limestone dark gray, medium crystalline, micaceous, silty, lumpy bedding,	

upper few inches stained moderate yellowish brown 3

207. Sandstone and siltstone very dusky red; sandstone medium-grained, irregular bedding; top of interval, pale red (10 R 6/1) cross-bedded sandstone 86

206. Sandstone (95%) and limestone; sandstone very dusky red, fine- and medium-grained, irregular bedding; limestone light bluish gray in two lumpy beds in upper part of interval 56

205. Sandstone pale red (10 R 6/1), coarse-grained, cross-bedded, arkosic, streaks of black mineral grains 43

204. Sandstone (70%), shale (20%), and limestone interbedded; sandstone and shale very dusky red; sandstone medium-grained; limestone moderate yellowish brown, nodular, near top of interval 37

203. Sandstone pale red (10 R 6/1) and reddish brown, former coarse-grained, latter medium-grained, cross-bedded, streaks of black mineral grains 38

202. Sandstone and siltstone similar to Int. 196 29

201. Sandstone pale red (10 R 6/2) similar to Int. 197, but contact with Int. 200 irregular 6

200. Sandstone and siltstone similar to Int. 196, but has small dark reddish-brown limestone nodules 32

199. Sandstone similar to Int. 197 19

198. Sandstone and siltstone similar to Int. 196 28

197. Sandstone pale red (10 R 6/2), coarse-grained, conglomeratic, rounded fragments of quartz and acid igneous rocks up to 3 inches in diameter; streaks of black mineral grains 35

196. Sandstone and siltstone dark reddish brown; sandstone medium-grained; siltstone shaly; soft interval 67

195. Sandstone pale red (10 R 6/2) in coarse-grained part, dark reddish brown in fine- and medium-grained part; arkosic, conglomeratic, rounded and subangular fragments of red granite, and dark-red porphyry; cross-bedded; irregular contact with Int. 194 32

194. Sandstone and siltstone interbedded; sandstone grayish red (10 R 4/2); siltstone dark reddish brown 10

193. Sandstone pale red (10 R 6/2) and dark reddish brown, former medium- and coarse-grained, latter fine-grained 55

192. Sandstone and shale; sandstone olive gray (5 Y 4/1), medium-grained, feldspathic, in 6-foot beds at top and bottom of interval, gray shale between; plant remains 19

191. Limestone and shale interbedded; limestone mainly pale brown to grayish brown, but two beds are medium gray; medium crystalline, nodular, up to 3 feet thick; shale moderate yellowish brown, noncalcareous 25

190. Sandstone top and bottom dark reddish brown, middle pale red (10 R 6/2), medium-grained, conglomeratic, rounded fragments of quartz, and granite up to 3 inches in diameter 16

189. Shale (50%), sandstone (40%), and limestone; shale very dusky red; sandstone dark reddish brown and lighter, fine- and medium-grained, irregular bedding; limestone dark gray, weathers moderate yellowish brown (moderate red on joint planes), several nodular beds 42

188. Sandstone, in lower 24 feet, grayish red with breaks of very dusky red shale, upper 14 feet pale red (10 R 6/2); coarse-grained, conglomeratic, cross-bedded 38

187. Sandstone (60%), shale (30%), and limestone, partly covered; sandstone medium-grained, soft; shale very dusky red; limestone dark gray, nodular, in shale in upper 4 feet of interval 23

186. Sandstone pale red (10 R 6/2), coarse-grained, cross-bedded, streaks of dark mineral grains, scattered subangular pebbles of igneous rock up to 2 inches in diameter; breaks of dark reddish-brown shale separate the interval into thirds 35

185. Sandstone (80%) and shale interbedded; sandstone dark reddish brown, medium-grained, arkosic; shale very dusky red, irregular bedding; limestone yellowish gray (5 Y 7/2), medium crystalline, in a 4-foot bed, 12 feet above base 77

184. Sandstone similar to Int. 182 60

183. Covered; perhaps soft sandstone 14

182. Sandstone grayish red (5 R 4/2), medium- and coarse-grained, arkosic, scattered fragments of granite up to 2 inches in diameter in upper foot; irregular contact with Int. 181 20

181. Shale (50%), sandstone (40%), and limestone interbedded; shale very dusky red; sandstone dark reddish brown, fine-grained; limestone medium light gray, weathers moderate yellowish brown, lies in basal 10 feet 61

180. Sandstone grayish red (5 R 4/2), medium-grained, arkosic; second prominent sandstone ledge on hillside 65

179. Sandstone and shale interbedded; sandstone olive gray (5 Y 4/1), weathers dark yellowish brown, micaceous, fine-grained; shale dark gray and very dusky red 13

178. Limestone and shale; limestone dark gray, weathers dark yellowish brown; shale dark gray, nodular with lumpy bedding 5

177. Middle partly covered; sandstone olive gray (5 Y 4/1), weathers dark yellowish

	Feet
brown; shale in upper part, very dusky red	23
176. Limestone medium gray, lower part weathers dark reddish brown, upper part weathers medium light gray; finely crystalline, lumpy bedding	5
175. Sandstone (90%), and limestone interbedded; sandstone grayish red (5 R 4/2 and 10 R 4/2), former medium-grained, latter fine-grained; some fine-grained layers show rain-drop impressions, irregular bedding; limestone dark gray, weathers light olive gray (5 Y 5/2)	10
174. Sandstone mainly very dusky red, fine- and medium-grained; basal 2 feet darker than greenish gray (5 GY 6/1) medium-grained, arkosic; a few thin limy beds at top of interval	51
173. Partly covered; shale dark gray, fissile	7
172. Sandstone (50%) and siltstone interbedded, lighter than brownish gray; sandstone medium-grained, arkosic	13
171. Sandstone grayish red (10 R 4/2), fine-grained, a few medium-grained beds somewhat lighter; 1 foot of dusky yellowish-brown shale at top	18
Offset to next gulch to south on Int. 170.	
170. Sandstone grayish red (5 R 4/2), slightly grayish cast, arkosic; lenses and pockets of finer-grained, redder sandstone	40
169. Sandstone and siltstone interbedded; light olive gray (5 Y 5/2); sandstone fine-grained; siltstone thin-bedded; both slightly calcareous, top weathers soft	42
168. Sandstone light brownish gray (5 YR 6/1), medium-grained, cross-bedded, feldspathic	7
167. Siltstone (60%) and sandstone interbedded; siltstone dark gray, muddy, micaceous; sandstone greenish gray, fine-grained; top 2 feet shaly	28
166. Sandstone slightly lighter than light olive gray (5 Y 5/2), fine-grained, biotitic, cross-bedded	14
165. Sandstone (70%) and shale; sandstone darker than greenish gray (5 GY 6/1), weathers light olive gray (5 Y 6/1), fine-grained; shale medium dark gray, silty	37
164. Sandstone darker than light brownish gray, fine-grained, cross-bedded; forms cliff	10
163. Siltstone and nodular limestone interbedded; siltstone light olive gray (5 Y 6/1); limestone medium dark gray, nodules up to 2 inches in diameter, surface appears rubbly	7
162. Sandstone (50%) and siltstone; sandstone similar to lower part of Int. 160; siltstone dark gray, thin-bedded, muddy	39
161. Sandstone pale brown, fine-grained, calcareous near base	2
160. Sandstone dark grayish green (5 GY 4/1) portion, fine-grained; greenish gray (5 Y 6/1) portion, medium- to coarse-grained; three beds of dark gray shale each 1 foot thick	31
159. Siltstone (70%), sandstone (20%), and dolomite interbedded; siltstone grayish black, much lumpy and irregular bedding; sandstone greenish gray (5 GY 6/1), fine-medium-grained, thin-bedded; dolomite similar to Int. 153, beds up to 1 foot thick	27
158. Sandstone greenish gray (5 GY 6/1), medium-grained, cross-bedded, slightly calcareous	6
157. Shale and dolomite interbedded; shale medium dark gray, weathers pale to dark yellowish orange, hard, dolomitic, forms competent beds; dolomite similar to Int. 153; a few thin beds of medium-gray sandstone	33
156. Covered	32
155. Dolomite similar to Int. 153	2
154. Sandstone and shale interbedded; sandstone dark greenish gray (5 GY 4/1); shale dark gray	6
153. Dolomite dark gray, weathers moderate yellowish brown, medium crystalline	2
152. Partly covered; mainly shale dark gray with thin beds of sandstone dark greenish gray (5 GY 4/1), fine-grained; 6 feet below top is 1 foot of dark-gray dolomite, weathers moderate yellowish brown	38
151. Sandstone dark greenish gray (5 GY 4/1), medium-grained, cross-bedded, scattered quartz pebbles up to .5 inch diameter	11
Offset south, to second arroyo northeast of the east end of Swissvale switch.	
150. Gypsum white to medium dark gray contorted, wedges out to south locally	100
149. Shale (70%) and dolomite; shale dark gray, weathers olive gray (5 Y 4/1); dolomite black and lighter than brownish black, banded, mainly in lower 20 feet of interval. At top of interval a 2-foot bed of porous limestone, weathers yellowish orange, coarsely crystalline	46
148. Sandstone greenish gray (5 GY 6/1), weethers moderate yellowish brown, medium- and coarse-grained, cross-bedded, upper layers quartzitic	24
147. Shale and limestone interbedded; shale dark gray; limestone (about 10 beds) dark gray, weathers lighter; muddy, other beds weather moderate yellowish brown. Interval is banded with these colors; contains *Myalina cuneiformis* .3 mile farther south	24
146. Sandstone darker than grayish green (10 GY 5/2), weathers dark reddish brown; medium- and coarse-grained, feldspathic, current ripple marks (strike NE.) at top	18

	Feet
145. Shale and limestone; shale dark gray and light olive gray (5 Y 5/2), soft; chips of very thin dark-gray limestone in float, weathers moderate yellowish brown	5
144. Sandstone similar to Int. 139	8
143. Partly covered; probably shale with a bed of limestone at top and bottom; limestone dark gray, weathers moderate yellowish brown	10
142. Sandstone lighter than dusky yellow green, medium-grained	6
141. Partly covered; probably shale, sandstone, and limestone; shale dark gray; sandstone dark yellowish brown in a thin bed at base of interval; limestone dark gray, weathers moderate yellowish brown, one bed near bottom of interval and two beds near top. (Forms crest of hogback)	17
140. Partly covered; sandstone light olive gray (5 Y 5/2), medium gray; beds about a foot thick	25
139. Sandstone similar to Int. 133, but conglomeratic, fragments of quartz and feldspar up to 1 inch in diameter	16
138. Partly covered; ledges of sandstone, light olive gray, medium-grained, some beds of shale	25
137. Sandstone similar to Int. 133, but loses white appearance to south	4
136. Shale dark gray, soft	5
135. Partly covered; ledges of sandstone, light olive gray, medium-grained	45
134. Shale dark gray, soft	8
133. Sandstone slightly darker than light olive gray (5 Y 6/1), weathers lighter; coarse-grained, forms a prominent light band on hillside	4
132. Sandstone and shale interbedded; sandstone dusky yellow green, fine- and medium-grained; shale dark gray, mainly in basal 4 feet	13
131. Sandstone dusky yellow green, medium-grained	5
130. Sandstone dark reddish brown and light olive gray, fine-grained, weathers soft	5
129. Sandstone greenish gray (5 GY 6/1), medium-grained, cross-bedded, massive; one thin bed of silty shale. Changes to siltstone and shale within 300 feet to south	29
128. Shale (60%), siltstone (20%), and sandstone interbedded; shale dark gray and dark greenish gray; siltstone light olive gray (5 Y 5/2), thin-bedded; sandstone dusky yellow green, weathers browner, fine- and medium-grained, beds up to 1 foot thick	38
127. Sandstone and siltstone interbedded; sandstone dusky yellow green, fine- and medium-grained, cross-bedded; siltstone light olive gray (5 Y 5/2)	9
126. Partly covered; ledges of shale and sandstone; shale dark greenish gray; sandstone light olive gray (5 Y 5/2), thick bed at top of interval	21
125. Sandstone (60%) and shale interbedded; sandstone dusky yellow green, medium- and fine-grained, cross-bedded, relatively thin beds; shale dark greenish gray	25
124. Shale dark greenish gray; interbedded sandstone light olive gray (5 Y 5/2), micaceous, medium- and fine-grained	13.5
123. Sandstone (70%) and shale interbedded; sandstone dusky yellow green and grayish red (10 R 4/2), medium-grained	18
122. Sandstone dusky yellow green, medium- to coarse-grained, feldspathic, cross-bedded, irregular contact with Int. 121	3
121. Sandstone (60%) and shale interbedded, dark reddish brown; sandstone beds and lenses become green along strike, fine- to coarse-grained, cross-bedded	7
120. Sandstone dusky yellow green, medium- and coarse-grained, cross-bedded, irregular contact with Int. 119, fragments of which occur in base	10
119. Sandstone grayish red (5 R 4/2), fine-grained, thin-bedded, soft	1–3
118. Shale and sandstone interbedded; shale medium gray; sandstone dusky yellow green, fine-grained, some beds quartzitic; thin band of grayish red (5 R 4/2) 2 feet below top	7.5
117. Limestone medium gray, moderate yellowish brown	0.8
116. Shale medium gray, with thin beds of fine-grained sandstone	6
115. Sandstone (80%) and shale interbedded, dark reddish brown; sandstone fine-grained	4
114. Sandstone dusky yellow green, top reddish because of fragments of red shale, fine-medium-grained, micaceous	15
113. Shale olive gray (5 Y 4/1) and dark gray, with thin beds of dark yellowish-green sandstone	5.5
112. Sandstone and siltstone interbedded; sandstone dusky yellow green, medium-grained; siltstone darker	7
111. Shale dark gray, thin-bedded; thin slabby sandstone dark yellowish brown, with plant remains; thin brecciated limestone, medium gray, weathers dark yellowish brown, near base of interval	8
110. Sandstone dusky yellow green, weathers browner, cross-bedded, irregular bedding, medium- and fine-grained; fine-grained beds softer	11.5
109. Siltstone dark greenish gray (5 GY 4/1) micaceous, thin-bedded	9
Offset 800 feet north to deep arroyo.	
108. Partly covered; chiefly sandstone (60%) and siltstone interbedded; sandstone	

	Feet
moderate olive brown, medium-grained; siltstone light olive gray (5 Y 5/2), very thin-bedded; possibly some shale	30
107. Limestone dark gray, weathers moderate yellowish brown, medium crystalline, hard	0.5
106. Sandstone and shale interbedded; sandstone grayish green (10 GY 5/2), medium- and coarse-grained, the latter beds resistant	52
105. Sandstone light olive gray (5 Y 5/2), medium-grained, biotitic, feldspathic, conglomeratic at top, fragments of red quartz up to 1 inch in diameter. (Locally forms divide between east and west forks of Wells Gulch)	4
104. Partly covered; chiefly sandstone light olive gray (5 Y 5/2) and browner than grayish green (10 GY 5/2), former beds fine-grained, latter medium- to coarse-grained; large fragments of black flint in some beds; possibly some shale or siltstone	40
103. Sandstone similar to Int. 101, but feldspathic and lacks shale	23
102. Sandstone dark reddish brown and very dusky red, former beds fine-grained, latter medium-grained, partly covered; thin shale very dusky red at top	21
101. Sandstone light olive gray (5 Y 5/2), weathers dark yellowish brown, medium-fine-grained, thin-bedded; 1-foot bed of shale, dark greenish gray (5 GY 4/1) near middle of interval	20
100. Shale (60%) and sandstone interbedded; shale grayish black; sandstone light olive gray (5 Y 5/2), fine-grained	17
99. Shale (90%) and limestone; shale medium dark gray, hard; limestone medium bluish gray, weathers moderate yellowish brown, thin	4
98. Sandstone light olive gray (5 Y 5/2), fine-grained, thin-bedded, soft	12
97. Sandstone darker than pale yellowish green, weathers lighter, medium-grained, some cross-bedding, but bedding is indistinct, noncalcareous; a few rounded pebbles of black basalt and red chert at base	17
96. Partly covered; sandstone and siltstone interbedded, mainly light olive gray (5 Y 5/2), but at least two 10-foot beds very dusky red; sandstone fine-grained; siltstone thin-bedded, micaceous	64
95. Sandstone grayish red (5 R 4/2), medium-grained, feldspathic, chlorite (?) fragments	6
94. Partly covered; sandstone (40%), siltstone (40%), and shale interbedded; sandstone grayish red (10 R 4/2); siltstone and shale mainly dark reddish brown, micaceous	68
93. Sandstone light olive gray (5 Y 5/2), weathers darker, medium- and coarse-grained, cross-bedded, lower 6 feet resistant, upper 5 feet finer-grained, softer, thin-bedded	11
92. Shale pale olive (10 Y 6/2), soft, capped by 2 inches of hard siltstone, dark greenish gray (5 GY 4/1)	3
91. Partly covered; siltstone (70%), sandstone (20%), and shale interbedded; siltstone and shale very dusky red; sandstone grayish red (10 R 4/2), medium-grained, cross-bedded, beds 2–3 feet thick, micaceous	32
90. Sandstone pale red (10 R 6/2) at top and bottom, greenish gray (5 G 6/1) in middle, medium-grained, feldspathic, cross-bedded	14
89. Sandstone (50%), siltstone (30%), and shale interbedded, very irregular bedding, beds pinch and swell within a few feet laterally; sandstone grayish red and very dusky red, medium-grained, arkosic, cross-bedded; siltstone and shale very dusky red	86
88. Sandstone grayish red (10 R 4/2), medium-grained, cross-bedded; fragments of Int. 87 in lower 1 foot	6
87. Siltstone and sandstone interbedded, very dusky red, irregular bedding; sandstone medium-grained, beds pinch and swell greatly	18
86. Sandstone pale red and grayish red (10 R 4/2), medium-grained, arkosic, cross-bedded, irregular contact with Int. 85; thin discontinuous shale break near middle of interval	14.4
85. Siltstone (60%), shale (20%), and sandstone interbedded; sandstone very dusky red, medium-grained, cross-bedded; siltstone same color; shale very dark red, except one bed near base which is greenish gray (5 GY 6/1)	23
84. Limestone and shale interbedded; limestone light brownish gray, weathers medium light gray and grayish brown, thin beds and nodules; shale mainly grayish red (10 R 4/2); contains spirifers and productids	7.5
83. Sandstone dark reddish brown, medium-grained, arkosic, cross-bedded, some beds quartzitic	7
82. Siltstone very dusky red, micaceous, weathers crumbly	8.4
81. Sandstone moderate red (5 R 5/4) with streaks of dark mineral grains; medium- and coarse-grained, cross-bedded, some beds conglomeratic	29
80. Sandstone lower part pale reddish brown, coarse-grained, arkosic, grades up into sandstone and shale very dusky red	35
79. Sandstone (70%) and shale, moderate red (5 R 5/4) and very dusky red, pinker than any interval below; sandstone medium-grained	34
78. Siltstone very dusky red, thin-bedded, micaceous	5
77. Covered, valley fill; perhaps sandstoen similar to Int. 75	37.5
76. Sandstone pale reddish brown, basal conglomerate of very dusky red sand-	

	Feet
stone fragments up to 6 inches diameter reworked from Int. 75; upper part contains pebbles of red quartz and igneous rocks up to 1 inch diameter	4
75. Sandstone and shale similar to Int. 73; slickensides	65
Faulting in Int. 75.	
84. Limestone pale brown, weathers pale yellowish brown, upper surface greenish black (5 G 2/1); contains echinoid fragments, *Derbyia* sp	1
73. Sandstone (70%) and Shale interbedded, very dusky red; sandstone medium-grained, arkosic, some cross bedding with beds up to 2 feet thick	38
72. Limestone greenish gray (5 GY 6/1), weathers moderate yellowish brown; medium crystalline, muddy, contains crinoid columnals and brachiopods	2.5
71. Sandstone and shale similar to Int. 69	30
70. Limestone and shale light olive gray (5 Y 6/1), weathers moderate yellowish brown; limestone medium crystalline, fragments of bryozoans, *Linoproductus* sp., and other brachiopods; shale light gray, 1 foot bed at base	2
69. Sandstone (60%) and shale interbedded; sandstone pale red (10 R 6/2), medium- and coarse-grained, arkosic, beds up to 2 feet thick; shale very dusky red	27
68. Shale light olive gray (5 Y 5/2), soft	2
67. Limestone medium gray, weathers moderate yellowish brown, lithographic, contains crinoid columnals, fragments of brachiopods	0.5
66. Shale pale red (10 R 6/2), weathers lighter	5
65. Sandstone (60%) and shale interbedded, very dusky red and grayish red (10 R 4/2); sandstone medium-coarse-grained, arkosic	26.6
64. Shale light olive gray (5 Y 5/2), grades up into grayish red	2
63. Shale (60%) and sandstone interbedded, very dusky red; a few limestone nodules near base; sandstone medium- and coarse-grained, arkosic, noncalcareous	44
62. Limestone light gray, lumpy bedding weathers rubbly; contains *Derbyia* sp., and other fossils	8
61. Shale light olive gray (5 Y 6/1)	2
60. Sandstone (80%) and shale interbedded, very dusky red; sandstone coarse- and medium-grained, arkosic, cross-bedded; a few thin beds of dark bluish-gray shale	42
59. Limestone light olive gray (5 Y 6/1), weathers lighter than moderate yellowish brown, lithographic, upper surface weathers dusky brown	6
Slickensides indicate minor faulting here.	
58. Covered; shale and sandstone, gray, soft	7
57. Limestone medium gray, weathers pale yellowish brown (10 YR 6/2), lithographic, wavy bedding, a few invertebrate fossils	3
56. Covered; possibly soft sandstone	2.7
55. Sandstone dusky yellow green, coarse-grained, feldspathic	8
54. Sandstone and shale similar to Int. 52	9
53. Limestone greenish gray (5 GY 6/1) mottled, lithographic, greenish-black coatings	1
Offset on Int. 52 to hills about 1 mile north of Wellsville where the limestone beds (Int. 43, 45, 47) form the crests of hogbacks.	
52. Sandstone (80%) and shale interbedded, grayish red (10 R 4/2) to very dusky red; sandstone medium-coarse-grained, arkosic	50
51. Limestone greenish gray (5 GY 6/1), medium crystalline, shaly and nodular at top and bottom, thick-bedded in middle; crinoid columnals	8
50. Shale dark greenish gray (5 GY 6/1), limy; contains *Chonetes* cf. *C. Dominus*	6
49. Sandstone light olive gray (5 Y 5/2), medium-grained, noncalcareous	4
48. Shale (60%) and sandstone grayish red (10 R 4/2), but grayish olive at base; shale silty; sandstone medium-grained, thin-bedded, hard	15.4
47. Limestone greenish gray, finely crystalline, lower part massive; upper part nodular soft; many *Derbyia* sp	5
46. Shale and limestone interbedded; shale dark gray; limestone in beds 1–2 inches thick. Probably Henbest obtained *Millerella* sp. from this bed	9
45. Limestone greenish gray	2
44. Sandstone (60%) and shale; sandstone light olive gray (5 Y 6/1), medium-grained; shale very dark red and yellowish gray	10
43. Limestone greenish gray (5 GY 6/1), weathers darker; finely crystalline	3
Fold and probably a fault.	
42. Shale and nodular limestone; shale pale reddish brown; limestone medium light gray, with dark greenish-gray (5 G 4/1) coatings. Shale contains crinoid columnals, bryozoans, *Derbyia crassa* (2% of individuals), *Derbyia* sp. (1%), *Chonetes* cf. *C. dominus* (small, 27%), *Dictyoclostus portlockianus* (13%), *Juresania* cf. *J. symmetrica* (small, 1%), *J. nebraskensis* (1%), *Linoproductus* (?) sp. (2%), *Spirifer occidentalis* (2%), *Cleothyridina orbicularis* (8%), *Composita subtilita* (38%), *Astartella concentrica* (2%), *Leda bellistriata* (1%), steinkerns of gastropod (1%), *Ameura major* (1%)	7
41. Sandstone (70%) and shale interbedded, pale red (10 R 6/2) and light olive gray; sandstone medium-grained	29
40. Shale and limestone; shale medium light gray and very dark red; limestone dark greenish gray, nodular weathers	

	Feet
soft; contains bryozoans, *Chonetina* sp., *Dictyoclostus* sp., *Composita subtilita*	8
39. Sandstone very dusky red and dusky yellow, medium-grained, ranges from quartzitic to soft	20
38. Limestone and shale interbedded; limestone gray, nodular contains *Myalina cuneiformis;* surface covered with much yellowish gray clay	4
37. Limestone pale olive, lower part soft and crumbly; upper part massive, algal (?); topmost bed darker and contains silicified *Derbyia* sp., *Linoproductus prattenianus, Composita elongata*	4
36. Shale medium dark gray, with thin beds of limestone, olive gray (5 Y 4/1), muddy; with 1-inch beds of grayish-black chert; contains *Plectogyra* sp. (15% of individuals), crinoid plates, echinoid spines, *Derbyia crassa* (2%), *Linoproductus* sp. (26%), *Composita* sp. (5%), *Aviculopecten* sp. (3%), *Annuliconcha* sp. (1%), *Straparollus catelloides* (?) (2%), ostracods (45%) namely: *Jonesina arcuata, Sulcella sulcata, Hastifaba pervulgata, Bythocypris* sp., *Cavellina* cf. *C. pulchella*	8
35. Sandstone and shale interbedded; partly covered; sandstone light olive gray (5 Y 5/2), weathers lighter, grades down into a conglomeratic sandstone; shale weathers dusky yellow green, soft	20.2
34. Sandstone very dusky red, medium-grained, calcareous, probably some shale in interval	20.4
33. Covered, probably shale	10.2
32. Sandstone light olive gray (5 Y 6/1), medium-coarse-grained, quartzitic, blocky fracture	3
31. Partly covered; ledges of soft, yellowish-gray sandstone	47
30. Sandstone similar to Int. 26, but not conglomeratic	6
29. Covered	19.5
28. Limestone dusky yellow, medium crystalline, argillaceous, sandy; *Derbyia* sp.	5
27. Covered	15.6
26. Sandstone between yellowish gray and very light gray, coarse-grained, conglomeratic, subangular fragments quartz and goethite	2
25. Covered	5
24. Sandstone light olive gray (5 Y 5/2), weathers dark yellowish brown, medium-fine-grained	19
23. Partly covered; sandstone light olive gray (5 Y 6/1), weathers darker, medium-grained, quartzitic	15
22. Covered; shale or sandstone, soft	8
21. Sandstone light olive gray (5 Y 5/2), weathers dark yellowish brown, medium-grained, quartzitic, contains lumps of goethite	2
20. Covered; dip slope	3±
Thickness of Minturn Formation	4198.6±

Porphyry sill or dike forms crest of ridge.

Kerber formation.

	Feet
19. Shale (60%) and sandstone interbedded; shale dark gray; sandstone olive gray (5 Y 3/2), weathers grayish brown; fine-grained	25

Porphyry sill; resembles Lincoln porphyry of Ten-mile district.

	Feet
18. Shale and mudstone; shale olive gray (5 Y 3/2); mudstone weathers grayish brown; hard, silty	5
17. Sandstone light olive gray (5 Y 5/2), weathers grayish brown; fine- and medium-grained, beds about 5 feet thick	15
16. Shale (80%) and sandstone interbedded; shale olive gray (5 Y 3/2); sandstone dark yellowish orange, fine-grained, soft	5
15. Sandstone (80%) and sandstone interbedded; sandstone dusky yellow, weathers dark yellowish brown to dusky yellow brown; fine- and medium-grained, massive, ledges, quartzitic near base; shale greenish-gray	19
14. Sandstone (80%) and shale interbedded; sandstone light olive gray (5 Y 6/1) in lower part, dusky yellow above, fine-medium-grained, soft; shale greenish gray, soft, in a 1-foot bed in upper 3 feet of interval	8
13. Shale medium gray and light olive gray (5 Y 5/2), weathers same; thin lenses of sandstone medium gray, fine-grained	9.5
12. Sandstone (90%) and shale interbedded; sandstone medium gray, with a few very light gray quartzitic beds, both weather medium light gray and dark yellowish brown, fine- and medium-grained, noncalcareous; shale dark gray, thin	9
11. Shale and coal; shale dark gray, chippy fracture; coal up to 1 foot thick	3.5
10. Siltstone dark gray, weathers dark yellowish brown and grayish orange, thin-bedded, noncalcareous	2.7
9. Shale dark gray, probably coaly beds	5
8. Mudstone dark gray, weathers dark yellowish orange, silty, some thin shale beds, noncalcareous	3.4
7. Sandstone medium light gray, weathers dark yellowish orange, fine- to coarse-grained, subangular grains of quartz	7
6. Shale and coal; shale dark gray, chippy fracture; coal thin, impure, near center of interval	3
5. Sandstone medium dark gray, weathers dark yellowish orange, fine-grained, much intergranular carbonaceous matter	7

	Feet
4. Sandstone (80%) and shale interbedded; sandstone dark gray, weathers lighter; fine-grained, in ledges up to 1 foot thick, a few plant fossils; shale dark gray, partly covered	12.7
3. Sandstone similar to that in Int. 2, quartzitic, reticulate pattern on weathered surfaces	6
2. Sandstone (70%) and shale interbedded; sandstone yellowish gray, weathers dark yellowish orange, fine- and medium-grained; shale dark gray	7
1. Breccia gray, weathers brown; matrix sandstone; fragments of limestone and chert up to 6 inches in diameter; lenticular	0–4.5
Total thickness of late Paleozoic	13,169.5±

Leadville limestone. Upper contact very irregular. Begin section about 300 yards south of U. S. Highway 50 on east side of Box Canyon, which is on south side of Arkansas River at Wellsville, Fremont County, Colorado.

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INSTITUTE OF TECHNOLOGY, ST. LOUIS UNIVERSITY, ST. LOUIS, MO.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, AUGUST 7, 1951

PROJECT GRANT 522/47.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 63, PAGE 881 AUGUST 1952

FORAMINIFERA IN GLACIAL TILL FROM NORTHEASTERN MONTANA

BY CLIFFORD A. KAYE

During a petrographic examination of a glacial till from northeastern Montana, well-preserved specimens of Cretaceous Foraminifera were found in the sandy fraction.

The sample of foraminiferal till was taken about 4 feet below the surface in a shallow cut on the south side of the east-west road crossing sec. 23, T. 29 N., R. 54 E. This is approximately 10 miles southwest of the small town of Froid, Montana, in the southern part of the Homestead quadrangle. The drift at this point is patchy and only 5 feet or less in thickness. The nonmarine Fort Union formation of Paleocene age crops out in many places in the area, and local sources of Cretaceous Foraminifera seem to be lacking.

The till is a compact, structureless, light-brown boulder clay and contains a large assortment of striated pebbles of Canadian origin. The till seemed typical of the region and was sampled for that reason. It has been tentatively correlated with early Wisconsin drift by Fred Jensen and Rober Colton, U. S. Geological Survey (oral communication).

To obtain the sand fraction, the till was first soaked in water and the clay softened and worked into suspension by kneading it with the fingers. The clay and silt fraction was then decanted off, and the sand and gravel residue, after repeated washings, was dried and sieved. Foraminifera were found only in the fraction passing the 80-mesh sieve (U. S. Standard, 0.177 mm) and were retained on the 100-mesh sieve (0.149 mm).

The Foraminifera were not abundant and consisted almost exlusively of *Globigerina*. The calcareous tests were whole and clean. The perforations and delicate structures of the shells were clearly visible. Besides *Globigerina*, two individuals of Rotaliidae were picked, and a collection was sent to Dr. J. A. Cushman. Unfortunately only the *Globigerina* were reported on by Doctor Cushman; the other species presumably were lost in transit. The specimens were identified as Cretaceous forms of *Globigerina*, but no specific identification was given.

The source of this delicate fossil detritus seems to be the marine Cretaceous Riding Mountain shale, which crops out in Canada far to the north of the sample locality. According to the Geological Map of the Dominion of Canada (1945), the closest outcrop of Cretaceous rocks in a northerly direction lies approximately 105 miles due north of the sample locality. There are, however, good reasons for believing that the glacial advance in this region was from the northeast; measured in this direction, the nearest Cretaceous outcrop is approximately 130 miles away.

The fragility of these Foraminifera points to the mildness of glacial wear and tear on some particles. Normally, the bulk of the finer grain-size fraction of a till is due to the trituration of rock fragments. The Foraminifera have obviously been spared any severe stress during this breakdown process and indicate that subglacial and englacial abrasion can, under some conditions, be slight enough to free delicate foraminiferal tests from their matrix and at the same time leave them intact.

Foraminifera were also found by Richard W. Lemke (oral communication) in an unoxidized grayish-blue till from a new highway cut about half a mile southeast of Velva, North Dakota. He reports that the Foraminifera were of Paleocene age and probably came from the foraminiferal Cannon Ball formation, which immediately underlies the till at this point.

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U. S. GEOLOGICAL SURVEY, SPOKANE, WASH.

PUBLICATION AUTHORIZED BY THE DIRECTOR, U. S. GEOLOGICAL SURVEY.